COMPUTER SIMULATION FOR DEVELOPMENT OF NON-CONVENTIONAL AIR CONDITIONING SYSTEMS

A Thesis Submitted

In Partial Fulfilment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

by

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to the

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

FEBRUARY, 1987

ME – 1987 – M – 20D – COM

To

My Parents

ACKNOWLEDGLMENTS

I wish to express my deep sense of gratitute and sincere regards to Dr. Manohar Prasad for his constant encouragement and invaluable guidance in the successful completion of this work.

I am also grateful to Dr. Keshav Kant who had been constantly in touch with the progress of my work.

My sincere thanks are due to Shri P.K. Misra and Shri D.K.S. Chauhan for their constant assistance throughout the period of experimentation.

I also thank Shri J.C. Verma and Shri S.C. Goel of the Structural Engineering Lab. for their unhesitating cooperation during experimental work.

I thank all my friends, George, Rajiv, Lokranjan, Samir, Sudan, Ashish, Sanjay and Ashok for making my stay at IIT Kanpur a memorable experience.

Thanks are also due to Swami Anand Chaitanya for his efficient and excellent typing.

IIT Kanpur   D. B. Zodpe

February, 1987

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NOMENCLATURE

T — Temperature, $^\circ C$

w — Specific Humidity or Humidity Ratio, kg_w/kg_a

x — Moisture Content of Sorbent, kg_w/kg_A

G — Mass Velocity, kg per hr. m^2

y — Depth of Sorbent Bed, m

ρ — Density, kg/m^3

θ — Time, hr.

h_D — Convection Mass Transfer Coefficient, kg_w per (hr) (sq.m.) (kg_w/kg_a)

A_v — Surface Area per Unit Volume, Sq.m./m^3

C — w_e/x, kg_A/kg_a

C_1 — $h_D A_v/G_a$, m^{-1}

C_2 — $h_D A_v C/\rho_A$, hr^{-1}

w_o, w_i — Inlet Humidity Ratio, kg_w/kg_a

x_o — Moisture Content of Adsorbent in Equilibrium with Inlet Air kg_w/kg_A

J_o — Bessel Function of First Kind and Zero Order

D_p — Equivalent Spherical Diameter, m

μ_a — Viscosity of Moist Air $kg_a/m.hr.$

p_s — Saturation Water Vapour Pressure, bar

p_A — Vapour Pressure of Adsorbed Water, bar

m — Slope, Non-dimensional

K — Y-Intercept, bar

C_p — Specific Heat

C   – Compression Efficiency

R.H. – Relative Humidity, Non-Dimensional

h,H – Enthalpy, kJ/kg

ε – Effectiveness of Heat Exchanger

η_H – Humidification Efficiency

P   – Pressure, bar

P_{wbs} – Saturation Vapour Pressure Corresponding to Wet-Bulb Temperature, bar

Subscripts

e   – Refers to Equilibrium State

a   – Refers to Dry Air

A   – Refers to Dry Adsorbent

ex – Refers to Exit Condition

i   – Refers to Inlet Condition

db – Refers to Dry-Bulb Temperature

wb – Refers to Wet-Bulb Temperature

g   – Vapour State

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CHAPTER I

INTRODUCTION

1.1 MOTIVATION

The depleting nature of conventional energy resources,
increasing cost of electrical energy and exorbitant cost of
conventional air conditioning systems have led to development
of alternate methods for the maintenance of desired environ-
mental conditions. Evaporative cooling, a primitive technique,
is one such endeavour gaining popularity these days. Factually,
this method is not a complete substitute for conventional air-
conditioning systems, but it has proved to be highly successful
for maintaining reasonable comfort conditions in offices,
residential buildings, production shops, theatres, ware-houses
etc.

Though ASHRAE Comfort chart [1] exhibits 21°C as the
best effective temperature for human comfort for summer condi-
tion, an effective temperature of 26°C is found to be a good
compromise between cost of energy and comfort [2]. This has
been supported by extensive work done in [3,4] where the
effective temperature of 26°C or even higher than this value
has been found to be comfortable for inhabitants of tropical
countries; but the air motion should be of the order of 0.7 m/s
or higher.

The evaporative cooling is found to be quite ineffective in the high humid environments such as those at coastal areas or in the rainy seasons. The environmental conditions of five major coastal cities of India are shown on a psychrometric chart in Fig. 1.1. The infiltration of humid air in such environments renders the high latent heat load in the room, i.e., on the conditioner coil. This increases compressor power as a relatively low evaporator temperature has to be maintained, besides the problem of frosting on the coil. If this is to be avoided then reheating of the air before supplying to the room is necessary. This is also quite an uneconomical solution.

Many researchers in the recent past have reported that the removal of moisture from air using sorbents followed by the sensible and evaporative cooling of air has a promising prospect in the field of air conditioning [5,6,7]. The present work is an attempt in this direction.

1.2 LITERATURE SURVEY

Many researchers are working in the area of dehumidification using sorbent materials. Their work is briefly described below.

A complete theoretical study of isothermal adsorbent bed has been done by Hougen and Marshall [8] using linear equilibrium relationship between adsorbate content of the gas and of the solid. The governing equations have been solved and the results have been presented in the graphical form.

B : BOMBAY (30·3°C ,77%)
C : CALCUTTA (32·4 °C ,74%)
M : MADRAS (35·3 °C ,63%)
T : TRIVENDRUM (28·2°C,82·2%)
V : VISHAKHAPATTANAM (33·9 °C , 67%)
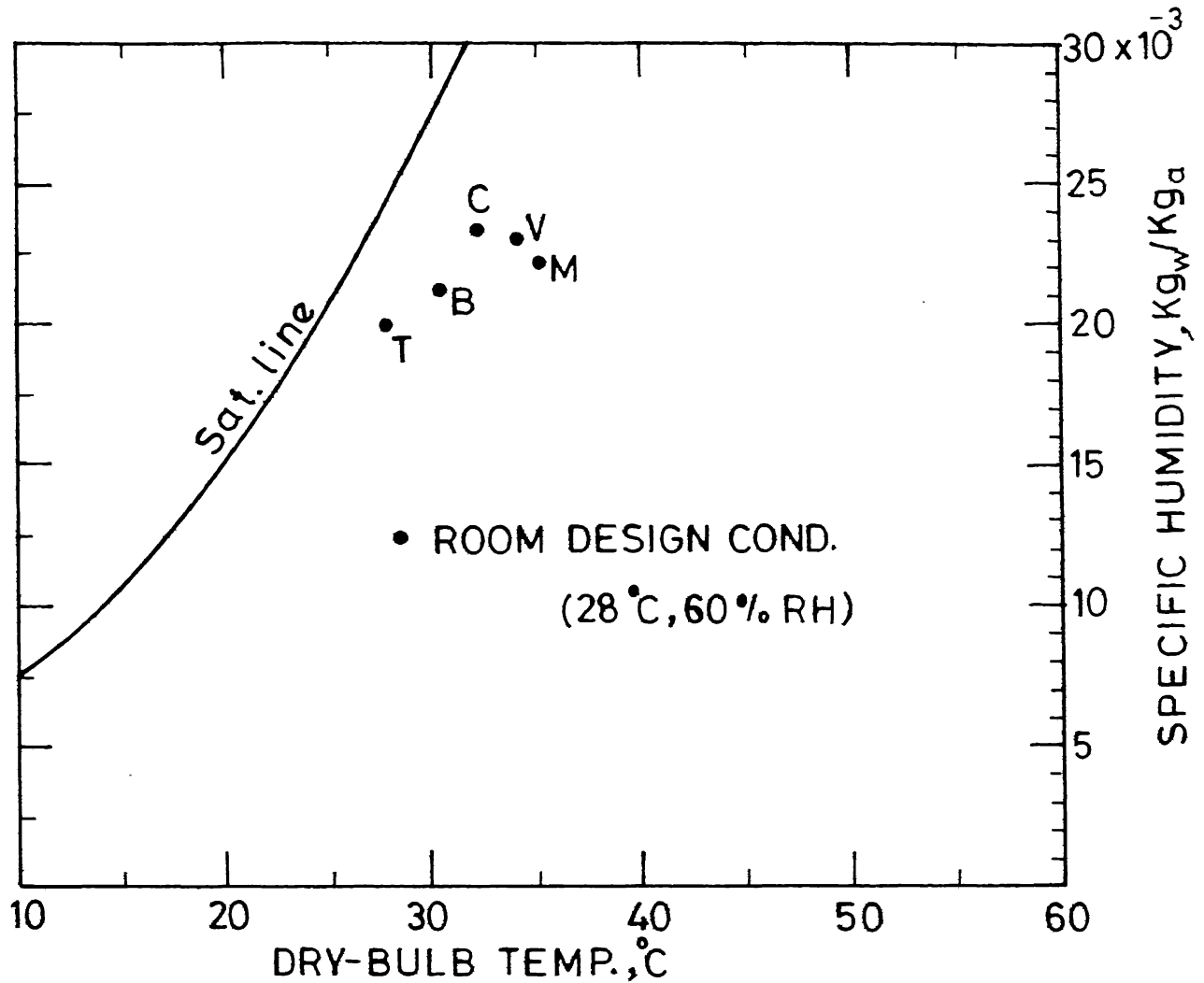
FIG·1·1 OUTDOOR DESIGN CONDITIONS FOR SOME MAJOR COASTAL CITIES OF INDIA

Threlkeld [9] has given equilibrium curves for sorbent materials and put forth the governing equations for isothermal and adiabatic stationary solid adsorbent beds. Solutions of these equations can be obtained if required system variables and material properties are known.

Ross and McLaughlin [10] have presented a method for predicting characteristics of dynamic adsorption system. They have carried out in all 24 tests for adsorption and desorption, for axial flow of air through the round bed having 6-16 mesh silica gel. They found out the effect of inlet air temperature, inlet relative humidity, face velocity and bed thickness on useful concentration of silica gel. But they did not consider the effect of grain size and bed geometry.

Olsen [11] has tried to investigate the potential for application of solar energy in warm climates. His report treats various modes of application of both liquid and solid dessicants for the space cooling. A special attention is given to the process of regeneration of dessicants; particularly the direct use of solar radiation to the dessicants. A combined system using dessicant for removing moisture and absorption refrigeration system to do the cooling was found to provide conditions for most favourable operation of both dessicants and the absorption refrigerator.

Mantell [12] in his book has studied adsorption process for many adsorbents, and discussed several applications of adsorption. He has lucidly explained a method of adsorbent bed

design and equipments for dehydration of air.

Brunauer [13] has discussed various theories related to physical adsorption process, surface and pore structure of adsorbent. However, the analysis is totally theoretical and lacks the experimental verification of results.

Young and Crowell [14] have given thermodynamic aspects of adsorption, theories of adsorption and nature of physical forces in adsorption process in detail. The techniques of measurement of adsorption isotherm are also discussed.

Prasad and Kumar [15] have studied dehumidification processes under adiabatic and cooled bed conditions for round and tray type beds using copper sulphate, calcium chloride, and silica gel as sorbent materials. Out of the three sorbents studied, silica gel was found to be most suitable for dehumidification. The time for its regeneration by a flat plate solar collector was found to be two hours as compared to one hour humidification period. They also studied five different air conditioning systems using adsorbent material for dehumidification.

Ayyash, Suri and Maheshwari [16] have tried to assess potential of various solar cooling systems as refrigerators and energy savers. For this purpose, a solar cooling system has been considered as a combination of an energy conversion and a refrigeration subsystem. Overall efficiencies of the various solar cooling systems are defined for direct quantitative comparison of different systems.

1.3 PRESENT WORK

Present work can be categorised in three parts. First part consists of theoretical computer aided analysis of isothermal adiabatic bed in transient state.

The maintenance of the isothermal bed is practically extremely difficult so the second part involves the experimental study of adiabatic silica gel bed for different mesh sizes and different bed thicknesses. The pressure drop across an adsorbent bed, being an important aspect for the selection of fan size, is measured. It is mainly a function of mesh size of adsorbent, face velocity of the air and bed thickness. The effect of these factors on the variation in pressure drop across an adsorbent bed are also studied in this part.

In the third part, four air conditioning systems using adsorbent material for the dehumidification are considered. A computer program has been developed which gives all the state points in the system and the mass of adsorbent required for the given outside condition of air. The performance of these systems is comparatively analysed for four major coastal cities of India namely, Bombay, Madras, Calcutta and Trivendrum.

Among them the system IV was found to be the best. It needs small amount of adsorbent as compared to other systems. Th power required for system IV was much smaller than that for the conventional vapour compression air conditioning system. The sar system is found to be the best for coastal areas.

CHAPTER II

DEHUMIDIFICATION OF MOIST AIR USING ADSORBENTS

2.1 SORBENT MATERIALS

A sorbent material is one that reduces the vapour pressure of water in contact with it below the saturation vapour pressure of water at that temperature, and the process is called sorption process. An affinity that exists between surfaces of certain materials and molecules of certain gases, causes gas molecules to adhere to the material surface. The sorption process always generates heat which is mainly the result of condensation of water vapour. All materials are sorbents to some degree. However, the term sorbent generally refers to those materials having a large capacity for moisture, relative to their volume and weight. Sorbent materials are classified into two categories.

(1) Absorbent

A sorbent which changes either physically, chemically, or both, during sorption process is called an absorbent. Lithium chloride is an example of solid absorbent. When water is absorbed by this material, the Lithium chloride is converted into a hydrate and reaches a saturation point at $LiCl_2.5H_2O$, after which the additional moisture gain tends to cause the material to loose its crystalline shape and dissolve in the water that was absorbed. Additional moisture causes a phase

change from solid to liquid. Liquid absorbents include
sulphuric acid, ethylene glycol etc.

(2) Adsorbent

A sorbent which does not change physically or chemically
during the sorption process is called an adsorbent. At no time
there is a phase change or solution of an adsorbent. An
activated alumina, silica gel, and activated charcoal are
the examples of adsorbents.

2.2 ADSORPTION PROCESS

A gas or vapour brought into contact with solid substance
has a tendency to collect on the surface of solid. This pheno-
menon is known as adsorption . Adsorption should be sharply
differentiated from absorption in the sense that adsorption
is commonly without chemical reaction between the adsorbent
and adsorbate, while absorption refers to more or less permanent
chemical reaction or phase change as a function of operation.
Adsorption may occur alone but also may be accompanied by
chemical reaction or the solution of the gas in the mass of
solid. In absorption, gas or vapour penetrates solid structure,
producing solid solution.

Adsorbent generally is an extremely porous solid foam
with large internal surfaces, its external surface comprising
only a small part of the total surface. This total area may
be as large as 1000 m^2 per gm of adsorbent and the internal
pore radii only few angstroms. Diffusion of the gas adsorbate
into ultramicroscopic pores and capillaries is easily confused

with the absorptive process in the interior of solid. However, as long as gas does not penetrate into the field of force that exists between atoms, ions, or molecules inside the solid, it is considered as adsorbed on the surface of solid even if this surface is an internal one.

Adsorption is of two types. "Physical adsorption" or "Van der Waals adsorption", a readily reversible phenomenon, is the result of intermolecular attractive forces between molecules of solid and the substance adsorbed. Atoms or molecules of a solid are held together by Van der Waals forces, valence forces etc. An atom in the interior of solid is subjected to equal forces in all directions, whereas an atom on the surface of solid is subjected to unbalanced forces, since the inward pull is greater than the outward force. As a result of these unbalanced forces, the surface of solid, just as that of liquid, will tend to decrease and surface tension will result. These unbalanced forces at the surface of solid (internal or external) cause the adsorbate to be attracted and held on solid. For example, when the intermolecular attractive forces between solid and gas are greater than those existing between molecules of gas itself, the gas will condense upon the surface of solid even though its pressure may be lower than the vapour pressure corresponding to that temperature. Such condensation will be accompanied by evolution of heat, the amount usually somewhat greater than latent heat of condensation of gas. The adsorbed substance does not penetrate within the crystal lattice of the solid and

does not dissolve in it but remains entirely upon the surface. If, however, the solid is highly porous containing many fine capillaries, as it is usually, the adsorbed substance will penetrate these interstices if it wets the solid and form a miniscus which is concave towards vapour phase. As we know from capillary theory, the vapour pressure over miniscus is lower than the normal vapour pressure of liquid by an amount equal to pressure exerted by the column of liquid in the capillary. Also, the smaller the radius of capillary, the greater the lowering of the vapour pressure. Hence amount of adsorption is still augmented. Physical adsorption is reversible in nature and the desorption can easily be done by lowering the pressure of gas phase or by raising the temperature of adsorbent.

"Chemical adsorption" or "chemisorption", is the result of chemical interaction between the solid and adsorbed substance. The strength of a chemical bond may vary considerably. But the adhesive force is generally much greater than that found in physical adsorption. The heat liberated during chemisorption is large, of the order of chemical reaction. The process is irreversible and generally a much higher temperature is necessary to remove the gases, the binding being so strong that the gas originally adsorbed comes off in a different state.

.2.3 <u>DESIRED PROPERTIES OF SORBENT MATERIALS</u>

Following are the desired properties of sorbent materials.

(a)   It should have suitable vapour pressure, i.e., sufficiently less than vapour pressure of the surrounding atmosphere.

(b)   Surface area per unit weight should be high.

(c)   Absorptive capacity should be high.

(d)   It should be, both physically and chemically stable within the range of operation.

(e)   It should resist contamination from impurities.

(f)   If they are used in a fixed bed through which liquid or gas is to flow, neither must they offer too great a pressure drop for flow nor must they easily be carried away by the flowing stream.

(g)   It should be non-corrosive, non-toxic, odourless and inflammable.

(h)   It should be capable of regeneration/reactivation with methods and temperatures available.

(i)   It should be available in abundance at low cost.

(j)   Its storage and handling should be easy.

2.4 <u>DEHUMIDIFICATION OF MOIST AIR BY A STATIONARY ISOTHERMAL</u>
    <u>ADSORBENT BED</u>

If the moist air passes through an adsorbent bed, the dehumidification of air occurs if humidity ratio w of air is greater than the equilibrium humidity ratio w_e of moist air with adsorbent. Similarly, the sensible heat transfer may

occur if a temperature difference exists between the air and adsorbent. For this analysis stationary adsorbent bed and isothermal condition of bed is assumed. The moisture content x of the adsorbent will vary with time and position within the bed. Evidently the heat and mass transfer will be of unsteady nature. Fig. 2.1 shows a schematic adsorbent bed of unit cross-sectional area. The bed is composed of small granules of the adsorbent material. The commercial dry silica gel contains about 5% of moisture which cannot be removed during regeneration process. It is usual practice to add this amount in the dry silica gel mass for analysis purposes.

The water material balance can be written as,

$$G_a w = G_a[w + \left(\frac{\partial w}{\partial y}\right) dy] + \rho_A \, dy \left(\frac{\partial x}{\partial \theta}\right) \tag{1}$$

This gives,

$$- G_a \left(\frac{\partial w}{\partial y}\right) = \rho_A \left(\frac{\partial x}{\partial \theta}\right) \tag{2}$$

For rate of adsorption we can write,

$$- G_a \left(\frac{\partial w}{\partial y}\right) = \rho_A \left(\frac{\partial x}{\partial \theta}\right) = h_D \, A_v \, (w - w_e) \tag{3}$$

Equation (3) gives,

$$\left(\frac{\partial w}{\partial y}\right) = - \frac{h_D \, A_v}{G_a} (w - w_e) \tag{4a}$$

$$\left(\frac{\partial x}{\partial \theta}\right) = \frac{h_D \, A_v}{\rho_A} (w - w_e) \tag{4b}$$

For isothermal case, w_e is approximated as a linear function of x,

$$w_e = Cx \tag{5}$$
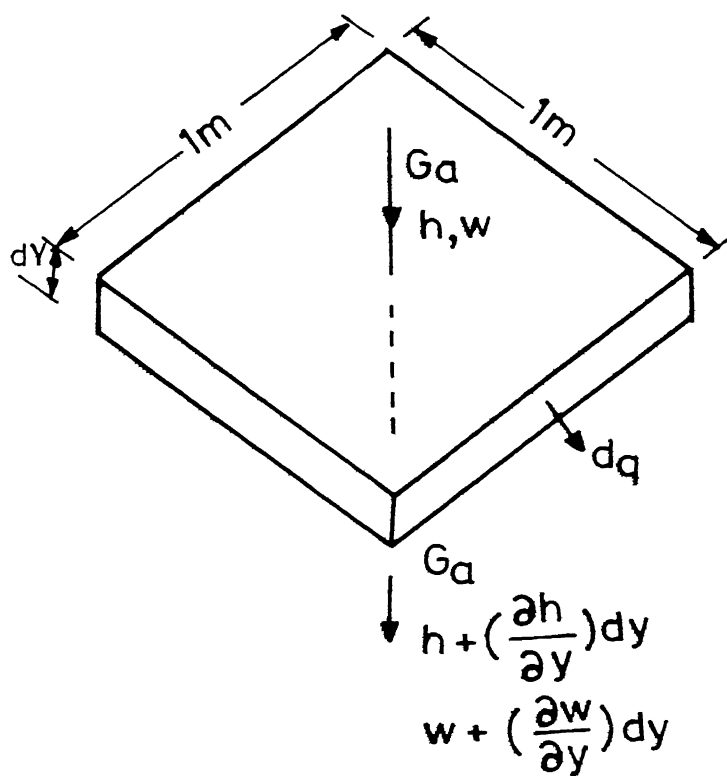
FIG. 2-1 SCHEMATIC ADSORBENT BED

Hence equations (4a) and (4b) become,

$$\frac{\partial w}{\partial y} = - C_1 (w - Cx) \tag{6}$$

and $\quad \frac{\partial x}{\partial \theta} = C_2 (\frac{w}{C} - x)$ (7)

where,

$$C_1 = \frac{h_D A_v}{G_a} \tag{8}$$

and $\quad C_2 = \frac{h_D A_v C}{A}$ (9)

Hougen and Marshall [8] have given the solutions to equations (6) and (7) under the following conditions. (a) The inlet air humidity ratio w_0 is constant for all values of θ, and (b) x = 0 for all values of y for θ = 0. The solutions are given by,

$$\frac{w}{w_0} = 1 - e^{-C_2\theta} \int_0^{C_1 y} e^{-C_1 y} J_0 (2i \sqrt{C_1 . C_2 . \theta . y}) \, d(C_1 y) \tag{10}$$

$$\frac{x}{x_0} = e^{-C_1 y} \int_0^{C_2\theta} e^{-C_2\theta} J_0 (2i \sqrt{C_1 . C_2 . \theta . y}) \, d(C_2\theta) \tag{11}$$

These solutions give values of w/w_0 and x/x_0 for given values of C_1, C_2, θ and y. But these solutions are also very complicated and involve integration of Bessel's functions for imaginary values. Till now graphical representation of solution of equations given by Furnas [17] were used for solving problems. In this thesis a computer program has been developed to solve above equations for preassigned values of C_1, C_2, θ, and y for θ varying from 0 to 240 minutes. Details of the program are

given in Appendix A. The program gives directly the values of w and x for given values of y, C_1, C_2, x_0, dry-bulb temperature of air, wet-bulb temperature of air at the time interval of 15 minutes upto 4 hours. The value of h_D required for calculating C_1 and C_2 are taken from semi-empirical equation given in Threlkeld [18],

$$h_D = 0.703 \ G_a \ (\frac{D_p \ G_a}{\mu_a})^{-0.51} \tag{12}$$

Values of D_p and A_v in F.P.S. units can be obtained from Hougen and Marshall [19]. These values are to be converted into S.I. units before using in program. Value of C is different for different isotherms and can be calculated from Threlkeld [20] after suitable conversion of units.

Above solutions of equations (10) and (11) help plot a condition line and instantaneous rate of heat removal so as to maintain adsorbent bed in perfect isothermal condition.

CHAPTER III

EXPERIMENTAL ANALYSIS OF ADSORBENT BED

3.1 SYSTEM DESCRIPTION

Figure 3.1 and photograph in Fig. 3.2 show an experimental set-up for the study of an actual performance of the adiabatic adsorbent bed. It comprises the following components,

(1) Fan,

(2) Heater,

(3) Water vapour generating chamber,

(4) Vertical round perspex duct and

(5) Mixing chamber.

The silica gel sampling was done on the basis of mesh size. The silica gel granules were passed through various meshes of different sizes to get them divided into three mesh sizes. The silica gel samples before and after regeneration are shown in Fig. 3.3. A detailed description of the above components is given later on.

The hot and humid condition of air is simulated, corresponding to that of coastal areas, with the help of the sensible heating by a heater and the humidification by evaporation of water. The simulated air is passed through silica gel granules kept in a vertical round perpex duct of 152 mm diameter.

CONNECTION FOR PSYCHROMETER

CONNECTION FOR MONOMETER

WIRE MESH

CONNECTION FOR PSYCHROMETER

ROUND PERSPEX DUCT

STRAINER
THERMOCOLE PACKING

MIXING CHAMBER

CONVERGING DIFFUSER

HEATER
COIL
FAN

VARIAC CONTROLLED
WATER HEATER
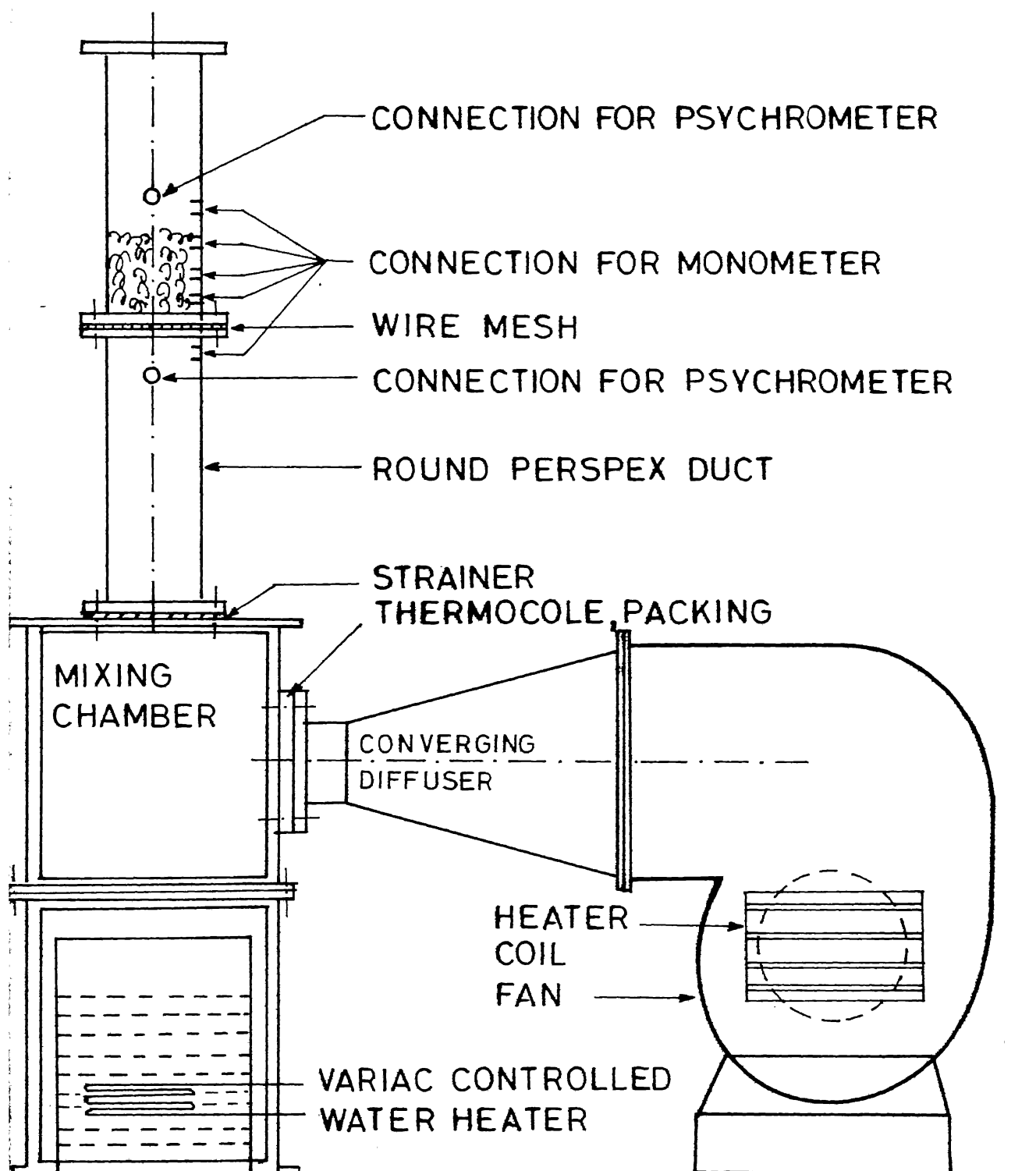
FIG.3·1 EXPERIMENTAL SET UP

Fig. 3.2: Photograph of an Experimental
Set-up.

Fig. 3.3: Silica gel Sample Before
and After Regeneration.

An electric oven has been used for the regeneration of silica gel granules.

3.2 SYSTEM COMPONENTS

3.2.1 Fan

It is a radial flow fan with volute casing. The converging diffuser is used to connect it to the mixing chamber.

Fan motor:

> Make: Premier Corporation Pvt.Ltd.
>
> Type: A.C., single phase, 50 c/s, 3/4 HP,
> 220-240 Volts, 5.2 Amp.

3.2.2 Heater

Heater was used for sensible heating of air at the inlet to fan. It has two heating elements of 3 kW and 4.5 kW along with thermostat to control the temperature. The heater has a fan for the circulation of air over the heater coil.

3.2.3 Water Vapour Generating Chamber

A metal container fitted with 2 kW heater is fabricated. It is kept inside the mixing chamber. The heat input to water is controlled by a variac.

3.2.4 Round Perspex 'Duct (Test Section)

Two flanged round perspex ducts are used. They are joined at their flange with nuts and bolts having wire mesh between two flanges to support adsorbent bed. Each duct is 450 mm long and having 152 mm diameter. The two Flanges

(220 mm x 220 mm) are fixed to each duct at both the ends. Holes are provided on the duct for the measurement of temperature, pressure and humidity.

3.2.5 Mixing Chamber

The hot air and water vapour were mixed in the mixing chamber to simulate hot and humid air sample. The mixing chamber is a wooden box of 430 mm x 335 mm x 450 mm dimensions. It is connected to the fan for hot air supply, and to the vapour generating chamber for water vapour. A strainer is fitted between mixing chamber and the test section so as to get uniform velocity of air across entire cross section of the duct.

3.3 INSTRUMENTATION AND MEASUREMENTS

3.3.1 Temperature and Humidity Measurement

Atkins thermocouple digital psychrometer was used for temperature and humidity measurement. It has a small fan for the suction of air from the test section for which the temperature and humidity are to be measured. It gives digital display of dry-bulb temperature and wet-bulb depression. These values were used for calculation of various psychrometric properties. Other particulars of this psychrometer are

Range   : $20^{\circ}C$ to $100^{\circ}C$

Accuracy   : ± 3 ℅

3.3.2 Air Velocity Measurement

Velocity of air through test section was measured by calibrated Vane type anemometer. The specifications for the

anemometer are,

Least count   : 1 meter

Range   : 0 - 100000 m

Windspeed   : 1 - 15 m/s

3.3.3 Pressure Measurement

Pressure drop across adsorbent bed was measured by U tube, red fluid manometer.

Range of Monometer : $4\frac{1}{2}$ in. of water

Least count   : 0.1 in. of water

3.4 TEST PROCEDURE

Two types of experiments were carried out on the same set-up.

(a) Experimental Study of Dehumidification Characteristics of Silica gel Bed

In this experiment the variation in dry-bulb temperature and specific humidity of the air coming out of the adsorbent bed with respect to mesh size and height of the bed are studied at equal time intervals.

Experimental Procedure

The water heater in vapour generating chamber, heater and fan were started about half an hour before the starting of the experiment to ensure constant air condition to adsorbent bed. At the start of an experiment the inlet condition of air to the adsorbent bed is noted down. Then reactivated silica gel of

particular mesh size is kept in the duct upto required bed thickness. Fan speed is reduced for a moment while putting the silica gel in the duct to avoid flying of granules. Again the fan speed is restored to desired value. Readings of dry bulb-temperature and wet-bulb depression were taken at the interval of 5 minutes with the help of digital psychrometer. The first reading was taken after two minutes because of rapidly varying nature of values. Experiment was carried out for 2 hours. Then the adsorbent was put in the oven set at $110^{\circ}C$ for regeneration. Its regeneration was ensured through colour change. Then the same experiment was carried out for different required combinations of mesh size and bed thicknesses. Three mesh sizes (U.S. standard) of silica gel; 19.0 mm - 12.7 mm, 12.7 mm - 9.51 mm, and 9.51 mm - 6.35 mm were tried. All the above mesh sizes were studied for three bed thicknesses; 75 mm, 115 mm and 150 mm. Fan speed was maintained constant through out the experiment.

(b) Experimental Study of Variation of Pressure Drop Across a Silica gel Bed

In this experiment variation in the pressure drop across silica gel bed with respect to mesh size, bed thickness and face velocity is studied.

Experimental Procedure

Adsorbent bed of required mesh size and bed thickness is made and the fan is started. The pressure drop across the bed and the velocity of air coming out of the test section are measured

by a manometer and anemometer respectively. The readings were repeated for four fan speeds. The same experiment was repeated for different combinations of mesh size and bed thickness. The fan speed was changed by variac. Pressure drop across the wire mesh was found to be approximately 0.1 in. of water for all speeds. It was deducted from the reading of pressure drops taken.

CHAPTER IV

SOME PROPOSED SYSTEMS AND THEIR COMPARATIVE ANALYSES

4.1 DESCRIPTION

Dehumidification using solid adsorbents can be performed
in either static or dynamic mode. In the former, the air
immediately covering the adsorbent gets dried initially and
subsequently through natural convection and diffusion distant
air is also dried.

Dynamic dehumidification is done by forcing the air
through or over dessicant bed. As the air passes through or
over dessicant bed, it gives its moisture to dessicant and gets
dehumidified. Amount of dehumidification is a function of many
variables such as particle size of adsorbent, shape of bed,
depth of bed, flow rate of air etc.

4.2 SOME PROPOSED SYSTEMS

There are many dehumidification and cooling systems
suggested by various researchers [6,7]. In the present case
four new systems which look promising, have been considered and
analysed. For comparison of these systems; the inlet air condi-
tion, room condition, temperature rise in the room, specific
humidity rise in the room, and the effectiveness of the heat
exchangers are maintained same, and mass flow rate of air required,
mass of adsorbent required, conditions at various state points,

amount of heat removal in the heat exchangers etc. have been found out for each system. The mass of the adsorbent, heat removal in heat exchangers, number of equipments involved in the system, and simplicity of the system are used as a criteria for selection of the best system.
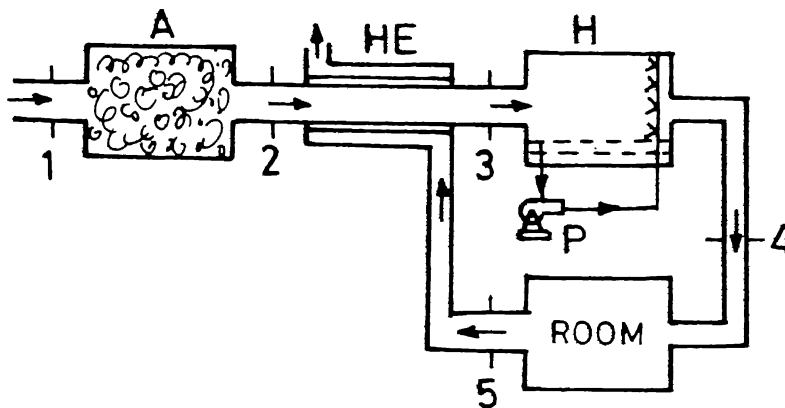
To accomplish the above, a computer program has been developed which gives all state points, mass of air required, mass of adsorbent required in adsorbent beds, compressor power required for the conventional vapour-compression air conditioning system and heat capacities of heat exchangers for a given ambient and room condition. The results are discussed later on. The procedure to predict various quantities are presented in Appendix B.

4.2.1 SYSTEM I

System I is a single-stage system, stage consisting of an adsorbent bed and a heat exchanger. Ambient air at state 1 is adiabatically dehumidified upto state 2 while passing through an adsorbent bed. This hot and dehumidified air at state 2 is sensibly cooled upto 3 with the help of room air in a heat exchanger; the room air being colder than ambient air. The air at state 3 is humidified in a spray chamber having a constant wet-bulb temperature process to state 4. Thereafter the air is sent into the room where it gets heated and humidified to state 5. The system arrangement and the psychrometric representation of the system are shown in Figs. 4.1(a) and 4.1(b). The iterative nature of calculations involved, is given in Appendix C.

1 : AMBIENT AIR
A : ADSORBENT BED
HE : HEAT EXCHANGER
H : HUMIDIFIER
P : PUMP
RD: ROOM DESIGN COND.

(a) SYSTEM ARRAGEMENT

$\epsilon = 0.85$
$\eta_H = 0.82$

1 AMIENT
(35°C, 75%)

(28.0°C, 61.54%)
RD
5

4

3

2

SPECIFIC HUMIDITY, Kg_w/Kg_a

30×10^{-3}

20

10

DRY-BULB TEMP, °C

10   30   50   70   90

(b) THE PROCESSES ON PSYCHROMETRIC CHART

FIG. 4.1 SYSTEM I
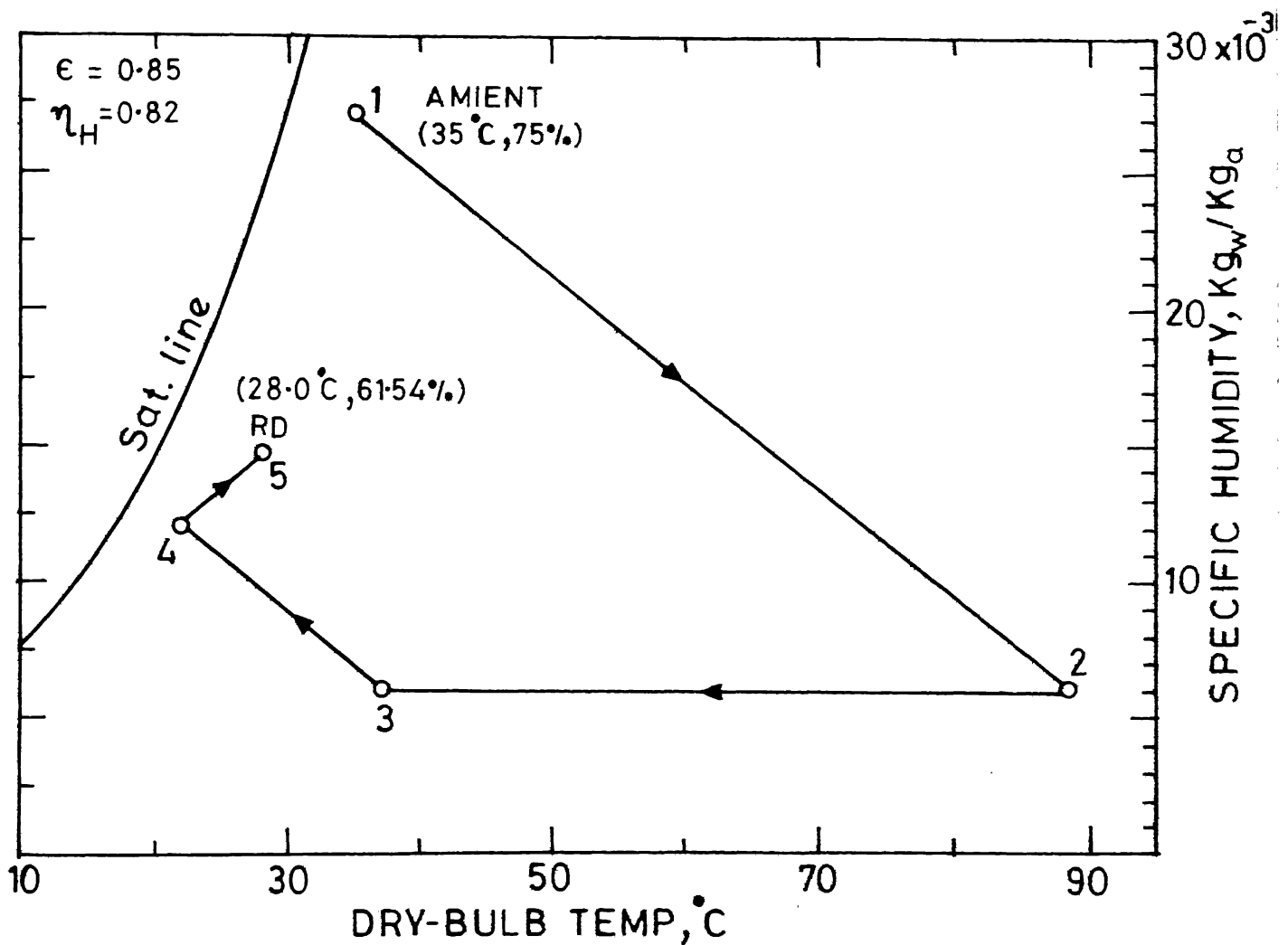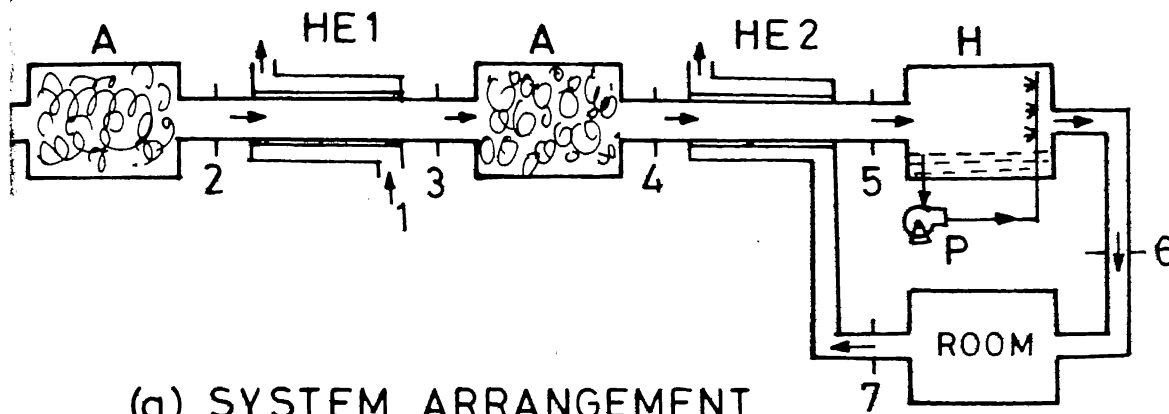
4.2.2 SYSTEM II

System II is a two-stage system, each stage consisting of an adsorbent bed and a heat exchanger. Ambient air at state 1 is adiabatically dehumidified upto state 2 while passing through an adsorbent bed. This air is sensibly cooled upto 3 in a heat exchanger using ambient air. Again this air at state 3 is adiabatically dehumidified in an adsorbent bed upto state 4. This air is cooled with the room air upto 5 in a heat exchanger, the room air being colder than the ambient air. The air at this state 5 is passed through a spray humidifier which follows a constant wet-bulb line rendering it at state 6. This air (state 6) is sent into the room where it gets heated and humidified upto 7 due to room load. The system arrangement and psychrometric representation of the processes are shown in Figs. 4.2(a) and 4.2(b).

4.2.3 SYSTEM III

System III is a three-stage system. The processes 1-2, 2-3, 3-4 are similar to system II. The air at state 4 is sensibly cooled with the ambient air in a heat exchanger upto state 5. The air at state 5 is adiabatically dehumidified upto 6 in an adsorbent bed. The air at 6 is sensibly cooled upto 7 with the room air, which is colder than ambient air, in a heat exchanger. The air at state 7 is sent through a spray humidifier where it gets humidified upto 8 at constant wet-bulb temperature. The air at state 8 is sent into the room to take the cooling load in room, where it gets heated and humidified upto state 9.

1 : AMBIENT AIR
A : ADSORBENT BED
HE: HEAT EXCHANGER
H : HUMMIDIFIER
RD: ROOM DESIGN COND.
P : PUMP

(a) SYSTEM ARRANGEMENT
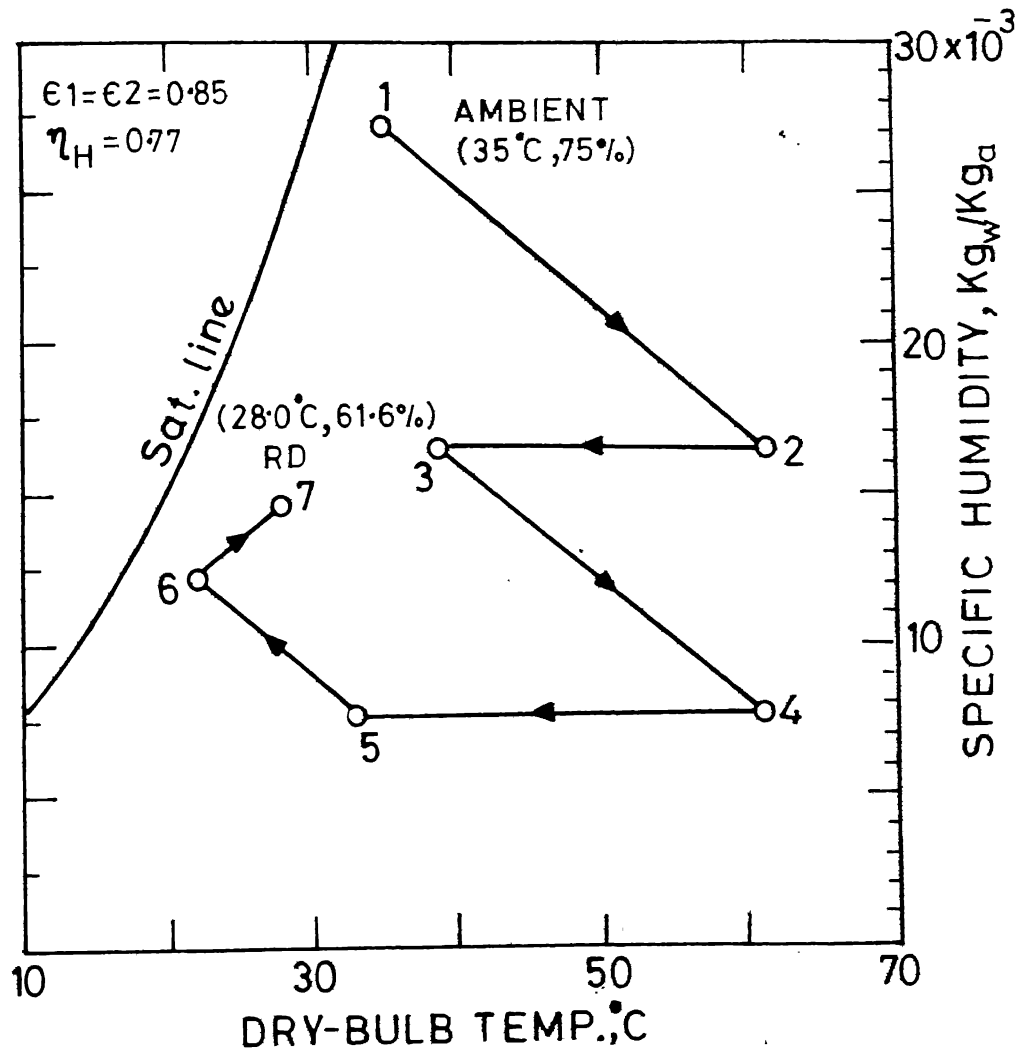
(b) THE PROCESSES ON PHYCHROMETRIC CHART

FIG. 4·2 SYSTEM II

The arrangement of the system and its psychrometric representation are shown in Fig. 4.3(a) and 4.3(b).

4.2.4 SYSTEM IV

This system is a hybrid system having a conventional air conditioning coil to cool the effluent air from the adsorbent bed. The ambient air at state 1 is cooled to 6 by passing it through an adiabatic humidifier. Then 20% of the ambient air at state 1 is mixed with the 80% of the recirculated air (state 2), from room resulting in a state 3 of air. The mixture air is passed through an adsorbent bed where it gets adiabatically dehumidified to state 4. The air at state 4 is cooled to state 7 by using cooled air (by humidification of ambient air) at state 6. The sensible cooling from 7 to 5 is done by vapour-compression refrigeration system. The air at state 5 is sent to the room where it gets heated and humidified due to room load and reaches room condition, state 2. The arrangement of the components for the system and psychrometric representation of the system are shown in Fig. 4.4(a) and 4.4(b) respectively.

To compare the performance of System IV and equivalent conventional vapour-compression air conditioning system, the compressor power required for the hybrid system and the conventional air conditioning system is computed. The systems are also analysed for the worst hot and humid condition of T_{db} = 35°C and T_{wb} = 31.0°C. Equivalent conventional vapour-compression air conditioning system which is used for above comparison is described below.

1 : AMBIENT AIR
A : ADSORBENT BED
HE: HEAT EXCHANGER
H : HUMIDIFIER
R : ROOM DESIGN COND.
P : PUMP
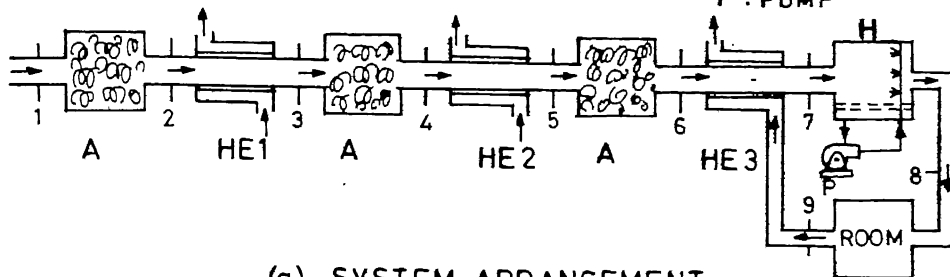
(a) SYSTEM ARRANGEMENT
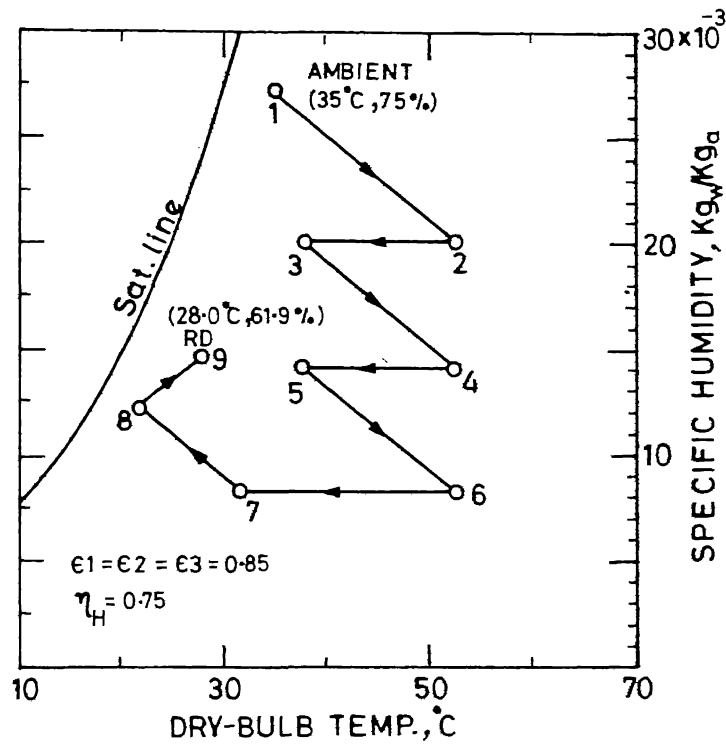
(b) THE PROCESSES ON PSYCHROMETRIC CHART

FIG. 4·3 SYSTEM III

(a) SYSTEM ARRANGEMENT

1 : AMBIENT AIR
A : ADSORBENT BED
HE : HEAT EXCHANGER
RD : ROOM DESIGN COND.
P : PUMP
CC : COOLING COIL
EX : EXPANSION VALVE
COMP : COMPRESSOR
C : CONDENSER

32

20 % AMBIENT AIR

20 % EXHAUST

COOLING WATER

$\epsilon = 0.85$
$\eta_H = 0.8$

AMBIENT (35°C, 75%)

Sat. line

RD (28.0°C, 67%)

(b) THE PROCESSES ON PSYCHROMETRIC CHART

DRY-BULB TEMP., °C

SPECIFIC HUMIDITY, Kg_w/Kg_a

30×10^{-3}

FIG. 4·4 SYSTEM IV

GATEWAY

4.3 EQUIVALENT CONVENTIONAL AIR CONDITIONING SYSTEM

The system and its psychrometric representation are shown in Fig. 4.5(a) and 4.5(b). In this system, the 20% of the ambient air at state 1 is mixed with the 80% of the room air at state 2, rendering air at state 3. The mixture is passed through the cooling coil having the bypass factor 0.2 and apparatus dew point T_9. Hence the air leaves the coil at state 10. Reheating process 10-5 is required to maintain the equivalence with the system IV. The process 5-2 is followed in the room.

To compare the compressor power required for hybrid System IV and conventional air conditioning system a typical refrigeration cycle is con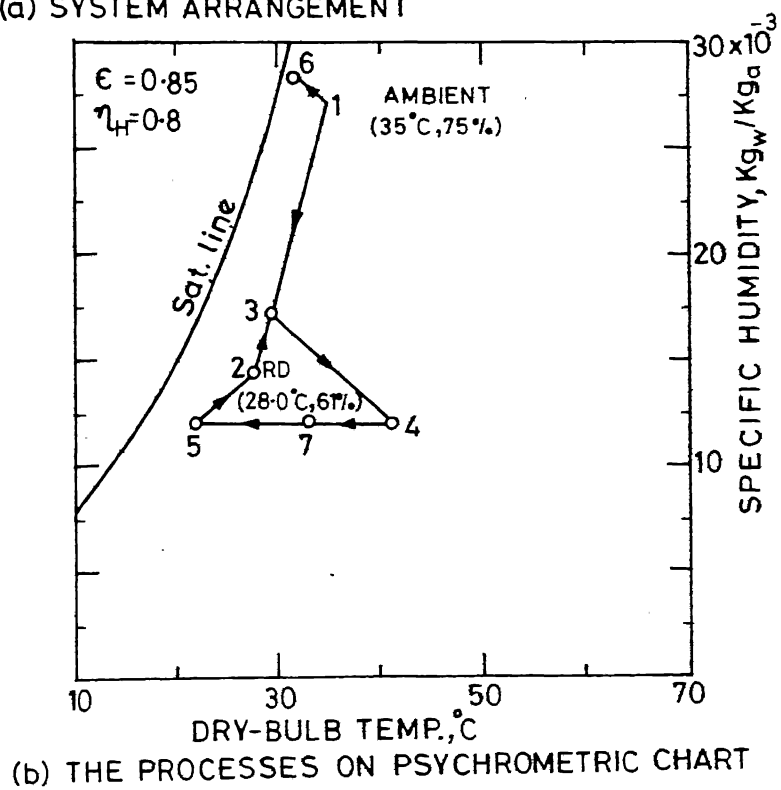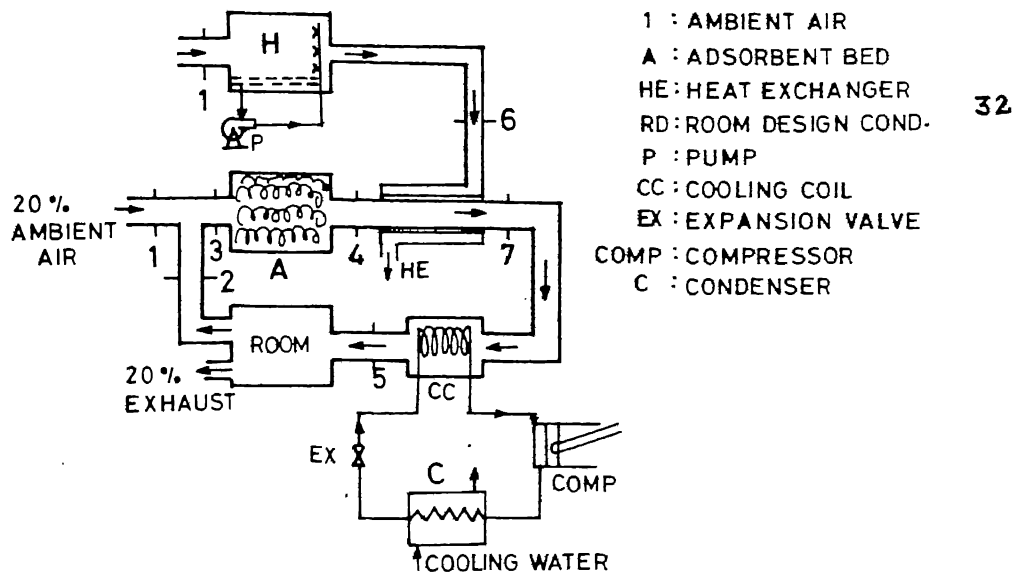sidered as shown in Fig. 4.6. R-22 refrigerent is used. The condensing temperature is assumed to be $40^{\circ}C$. The super-heating process 1-2 occurs in the suction line of compressor. The isenthalpic process 2-3, is throttling in suction valve of the compressor. The actual compression process in the compressor is shown by 3-4', assuming compression efficiency as a function of compression ratio. The isentropic compression is shown by 3-4. The process 4'-5 represents isenthalpic pressure drop due to throttling in discharge valve of the compressor. The desuperheating process in the condenser is shown by 5-6 and 6-7 is the heat removal due to condensation in the condenser. The pressure drop in the suction valve of compressor is assumed to be equivalent to difference between the saturation pressure at evaporator temperature and the saturation pressure corresponding to a tem-

A.C. COIL

20%
AMBIENT
AIR

REHEATER

1

3

2

10

ROOM

5

20%
EXHAUST

(a) SYSTEM ARRANGEMENT

COIL BF = 0.2

Sat. line

1 AMBIENT
(35°C, 75%)

3

2

ROOM DESIGN COND.
(28.0°C, 61.0%)

9 10 5

30 ×10⁻³

20

10

SPECIFIC HUMIDITY, Kg$_w$/Kg$_a$

0   20   40   60
DRY-BULB TEMP., °C

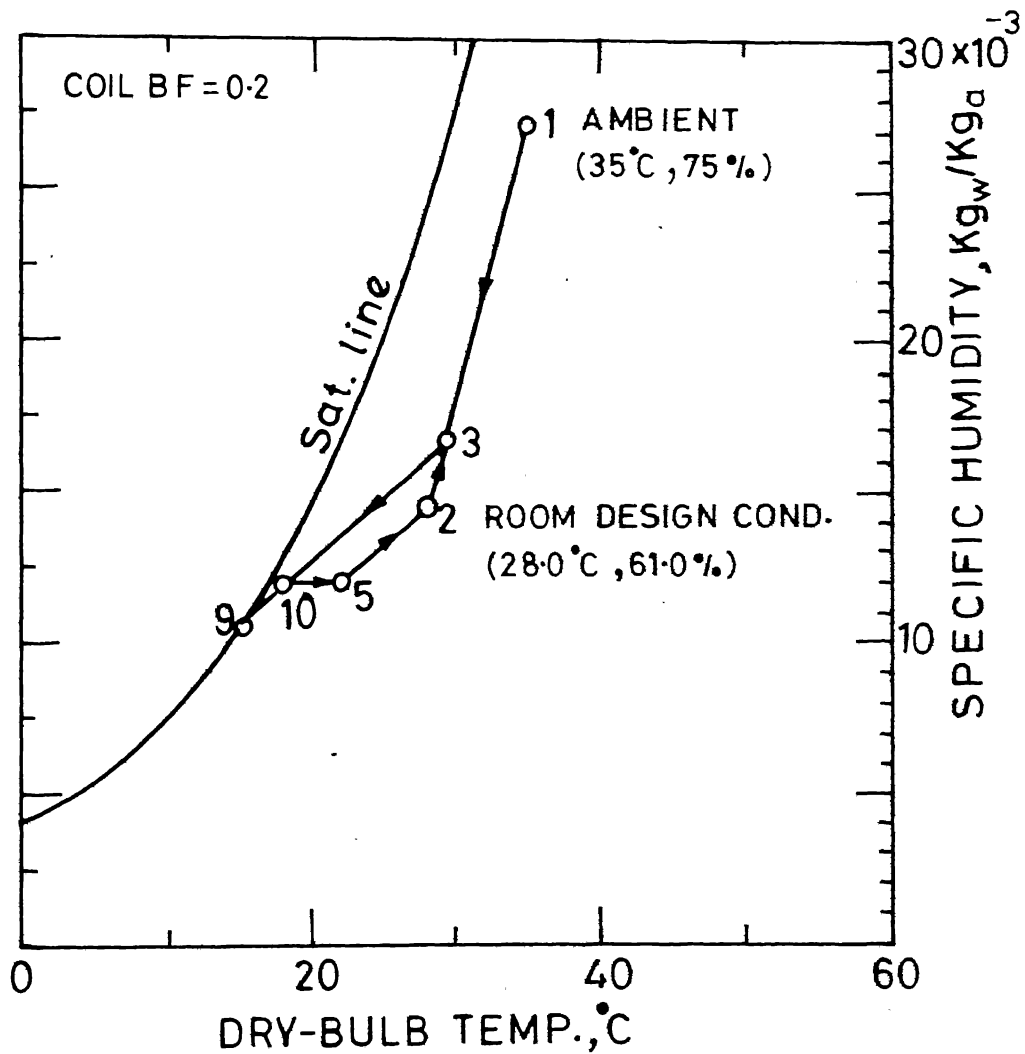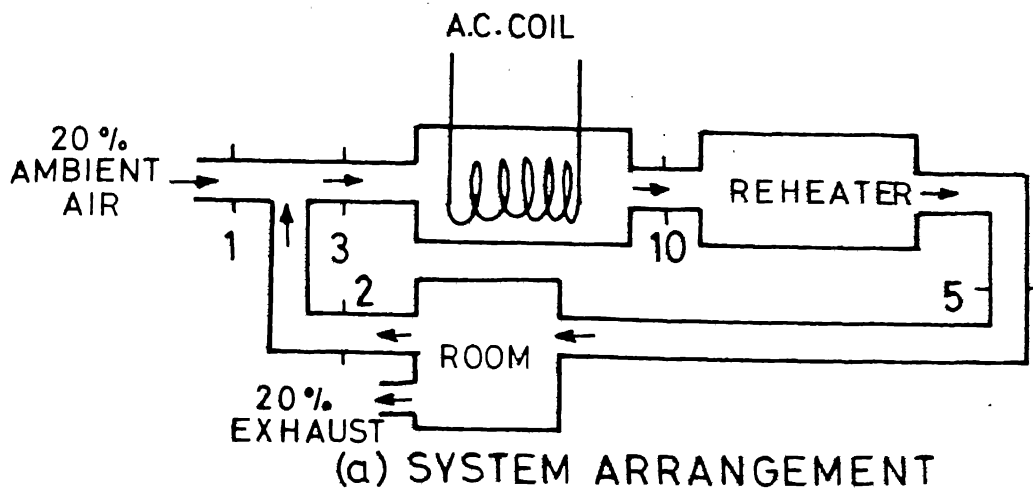(b) THE PROCESSES ON PSYCHROMETRIC CHART
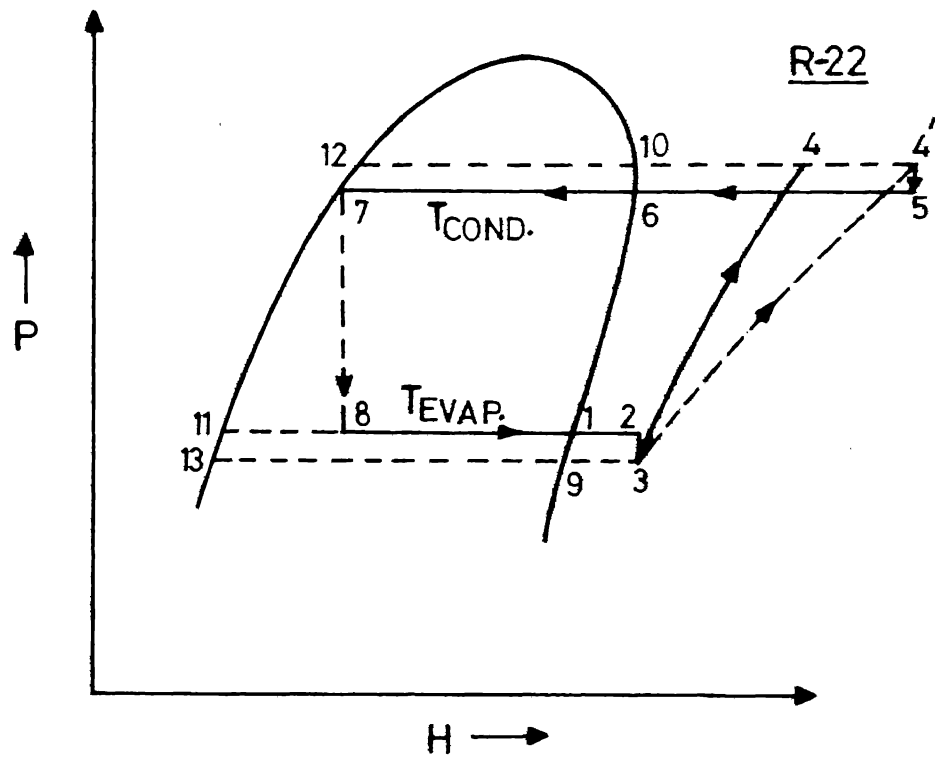
FIG·4·5 EQUIVALENT A/C SYSTEM

FIG·4·6 REFRIGERATION CYCLE USED FOR
CALCULATING COMPRESSOR POWER

perature $4^{\circ}C$ lower than evaporator temperature. Similarly, the pressure drop in the discharge valve is taken to be equivalent to a difference between saturation pressure at a temperature $4^{\circ}C$ higher than the condenser temperature and the saturation pressure corresponding to condenser temperature. State points 12, 10, 11, 13 and 9 are shown in the diagram even though they are not the part of refrigeration cycle because they have been used for computational work in the computer program.

4.4 PROCEDURE TO CALCULATE THE MASS OF ADSORBENT REQUIRED

The mass of adsorbent required in a dehumidifier depends on inlet and exit conditions of air, mass flow rate of air and the dehumidification period. The procedure given by Mantell [21] has been followed to calculate the mass of adsorbent. The steps are as follows:

1.   First the equilibrium moisture content x_1 of the adsorbent with the given inlet condition of air is read from the graph prepared in S.I. units from Threlkeld [22] as shown in Fig. 4.7. Similarly, the equilibrium moisture content x_2 of the adsorbent bed with the given exit air condition is found out. If the bed is 12 inch (300 mm) thick or more then the average moisture content of the bed can be taken as $\frac{x_1 + x_2}{2}$ kg_w/kg_A [21].

For example, referring to the Fig. 4.7, for the inlet air condition of $35^{\circ}C$ (p_{s_1} = 0.05628 bar) and w_1 = 0.0272 kg_w/kg_a (p_{A_1} = 0.04245 bar), x_1 = 0.41. Similarly, for the exit condition of $61.4^{\circ}C$ (p_{s_2} = 0.2136 bar) and w_2 = 0.0165 kg_w/kg_a
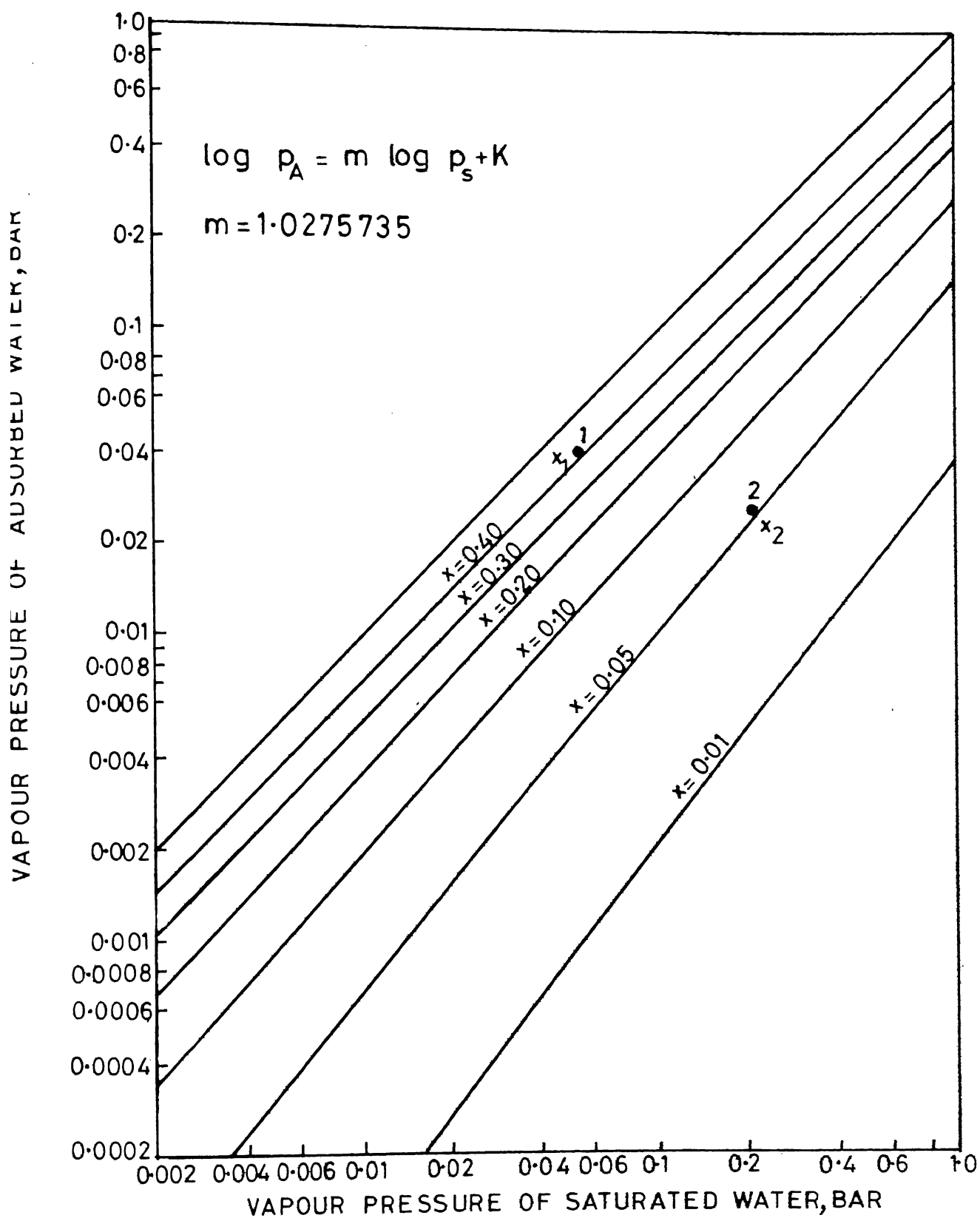
FIG. 4.7 VAPOUR PRESSURE OF WATER ADSORBED ON SILICA GEL

$(p_{A_2} = 0.02618$ bar)$;$ $x_2 = 0.055.$ This gives average moisture content of bed $= \dfrac{0.41 + 0.055}{2} = 0.2325$ kg_w/kg_A. The inlet and exit condition of air are shown by 1 and 2 in the Fig. 4.7 respectively.

To computerise the method lines for different values of x are assumed parallel to the line for x = 0.2. The equations of the line are assumed to be of the form $\log p_A = m \log p_s + K$ and the slope of the lines m is found to be 1.0275735. The value of K can be obtained from

$$ K = \frac{p_A}{(p_s)^m} = \frac{p_A}{(p_s)^{1.0275735}} $$

Knowing p_s and p_A from the known condition of air, the value of K is calculated. The value of equilibrium moisture content x can be obtained from a relation developed between K and x using curve fitting technique. This relation is given in Appendix B.

For the above mentioned example, values of x_1 and x_2 are found to be 0.4073 and 0.05946 respectively. Average value of moisture content of bed comes out to be 0.2325. The percentage error for calculating x_1 and x_2 comes out to be 0.65% and 8.10% , respectively whereas percentage error for calculating average value of moisture content comes out to be 0.37% , so the method is fairly accurate for the practical purpose.

2.   Knowing the mass flow rate of air and inlet and exit humidity ratios, amount of water to be removed is computed for the given humidification time period.

3.   The mass of adsorbent required to maintain the given outlet condition of air for a given humidification time period is determined by dividing the mass of water to be removed by average moisture content of the bed.

CHAPTER V

RESULTS AND DISCUSSIONS

5.1 STUDY OF DEHUMIDIFICATION BY A STATIONARY ISOTHERMAL ADSORBENT BED

A computer program is developed for the solutions of equation (10 and 11) of Chapter II to study the characteristics of an isothermal adsorbent bed. The results are given in Fig. 5.1 for .0764 m bed having $C_1 = 164.48/m$ and $C_2 = 7.74/h$. The adsorption rate is high upto 60 minutes indicated by low values of w/w_o. The low value of x/x_o also indicates that the bed is active upto that time. After this time the value of x/x_o starts increasing rapidly. Hence the bed tends to be saturated in around 180 minutes, $x/x_o \doteq 1$ and $w/w_o \doteq 1$.

The above mentioned program computes values of w/w_o, w, x/x_o and x at an interval of 15 minutes upto 4 hours, for the given values of inlet air dry-bulb temperature, wet-bulb temperature, C_1, C_2 and bed thickness. The program has been run for sample values and results are given in Appendix A. As this computer program eliminates the graphical estimation, it would serve as an useful tool for the general isothermal bed design.

5.2 ANALYSIS OF EXPERIMENTAL RESULTS

Experiments were carried out to study the dehumidification characteristics of silica gel in adiabatic condition. The effect of mesh size and bed thickness on dehumidification was studied experimentally at various time intervals. The inlet conditions have been simulated corresponding to those of the coastal areas and rainy season. Also the effect of mesh size, bed thickness, and face velocity on pressure drop across silica gel bed was studied. The results of the analysis are discussed below in details.

5.2.1 General Nature of Adsorption Curves

Figures 5.2 to 5.7 exhibits the variations in $T_{db_{ex}}$ and w_{ex} with time for different combinations of bed thicknesses and mesh size. In general, the nature of $T_{db_{ex}}$ curves shows sharp rise in $T_{db_{ex}}$ due to rapid adsorption of moisture in initial stages and later on decrease in $T_{db_{ex}}$ values. This is due to the fact that silica gel having high initial adsorption capacity liberates more heat of adsorption in the beginning because of higher values of heat of condensation and heat of wetting. As time increases bed goes on becoming saturated, resulting in reduced adsorption and hence reduced heat of adsorption. This results in a decreasing trend in $T_{db_{ex}}$ values. Theoretically speaking $T_{db_{ex}}$ should have maximum value at the beginning of operation, because there will be maximum rate of heat liberation at that instant, but this does not happen. This is because the bed being at lower temperature in the beginning acts as a heat sink and substantial part of the heat liberated

is used for sensible heating of the adsorbent bed. Later on, as the temperature of bed increases, a comparatively larger part of the heat of adsorption is used for raising the air temperature. The maximum temperature of air results after certain time lag which was found to be 10 minutes for almost all cases. Usually after 60 minutes $T_{db_{ex}}$ remained constant at a temperature a bit higher than the inlet air temperature, the difference being 2-5°C. This is due to the small adsorption taking place and the reverse heat transfer from bed to air.

The nature of the w_{ex} curves shows that a maximum rate of dehumidification occurs at the beginning and later on goes on decreasing till the bed becomes saturated. The general study of all w_{ex} curves shows that effective dehumidification occurs only upto 20 minutes (due to smaller thickness of the bed) and adsorbent should be taken for regeneration after that.

5.2.2 Effect of Bed Thickness on Dehumidification

Figures 5.2 to 5.4 exhibit the effect of bed thickness on dehumidification for various mesh sizes. The $T_{db_{ex}}$ curves in these figures have a higher peak for a thicker bed. This is quite natural because more amount of silica gel comes in contact with air as the bed thickness increases. Also due to a higher flow resistance the velocity of air passing through the bed reduces giving more time of contact between silica gel and air. The w_{ex} curves are also plotted for different bed thicknesses. The interesting characteristic of w_{ex} curves is that as bed thickness increases, time required for saturation

of the bed increases. As seen in Fig. 5.2, for silica gel of mesh size 9.51 mm - 6.35 mm, the bed of 75 mm thickness takes only 25 minutes for reaching saturation stage as against 45 minutes for 150 mm thick bed. It implies therefore, that an even larger bed thickness has to be used to have commercial application.

5.2.3 Effect of Mesh Size on Dehumidification

Figures 5.5 to 5.7 show time-wise variation of $T_{db_{ex}}$ and w_{ex} of dehumidified air for different mesh sizes for a particular bed thickness. The general nature of $T_{db_{ex}}$ curves for these figures shows that the air gets heated to higher temperatures with fine mesh size as compared to those with coarse mesh size. The former renders more pressure drop due to larger area of contact. Hence the mass flow rate of air through the bed is lowered causing more adsorption per unit weight of air flowing and more temperature rise. Also, for a given bed thickness, the bed of fine mesh size contains more mass of adsorbent than that of coarse mesh size. These factors lead to higher adsorption rates and hence higher temperatures for finer grade silica gel. For example, the maximum value of $T_{db_{ex}}$ for 9.51 mm - 6.35 mm mesh silica gel bed of thickness 115 mm is 53°C whereas for 19.0 mm - 12.7 mm it is 47°C. w_{ex} curves show that fine silica gel shows higher dehumidification as compared to coarse silica gel for a given bed thickness. For example, at the end of 15th minute,

w_{ex} value for 9.5 mm – 5.35 mm silica gel is 0.01875 kg_w/kg_a as compared to that of 0.023 kg_w/kg_a for 19.0 mm – 12.7 mm mesh silica gel; for a bed thickness of 115 mm. Figure 5.6 shows that silica gel of 19.0 mm – 115 mm mesh size is almost saturated at the end of 25th minute whereas silica gel of 9.51 mm – 5.35 mm gets saturated at the end of 50th minute.

5.3 EXPERIMENTAL STUDY OF PRESSURE DROP ACROSS AN ADSORBENT BED

Figure 5.8 shows the effect of mesh size, bed thickness and face velocity on the pressure drop across silica gel bed. The nature of curves is parabolic for different combinations of mesh size and bed thickness. For example, for a velocity of 1 m/s and mesh size 12.7 mm – 9.51 mm, the pressure drop across 75 mm bed is 16 mm of water and pressure drop across 150 mm bed is 22.86 mm of water. Similarly, for a given face velocity and bed thickness, pressure drop for fine grade silica gel is more than the coarse grade silica gel i.e., for a bed thickness of 115 mm and face velocity of 1 m/s, pressure drop for the 9.51 mm – 6.35 mm silica gel is 29.7 mm of water whereas for the 19 mm – 12.7 mm silica gel the pressure drop is 14.22 mm of water.

5.4 COMPARATIVE ANALYSES FOR THE PROPOSED SYSTEMS

The comparison of all the four systems in terms of state points, mass of adsorbent required, heat capacities of heat exchanger(s), mass of air required and the power required is presented in Table 5.1. The system IV is found to be the most suitable choice.

The mass of adsorbent required for this system is the least as compared to other systems. The fan capacity will be reduced due to the smaller mass of adsorbent in the system. Also the size of the regeneration chamber and the energy for regeneration will get reduced. Since the dehumidification of air $(w_1 - w_2)$ is quite low for system IV as compared to the other systems, the regeneration time would also be low. The temperature of the air leaving the adsorbent is quite low as compared to other systems, hence adsorbent bed will perform more efficiently.

The total power (for cooling and reheating) required for the conventional vapour-compression air conditioning system is 3.08 kW whereas the power required for system IV is 1.253 kW, if both systems are operating for worst ambient conditions of $T_{db} = 35^{\circ}C$ and $T_{wb} = 31^{\circ}C$.

The heat exchanger capacity required for the system is also quite low as compared to other systems. The evaporator-temperature required is moderate. Hence the problem of frosting on the coil is totally eliminated. From the thermodynamics point of view also system is quite good since significant amount of heat recovery (in form of using humidified ambient air in the heat exchanger for cooling) has been used.

For the other systems (I, II, III) mass of adsorbent required reduces as number of stages go on increasing. The system with higher number of stages has to handle air having high relative humidity as compared to the system having lesser

number of stages. But the system cost goes on increasing
for the higher number of stages because of more number of
equipments.

5.5 GENERALISED COMPUTER PROGRAM FOR FOUR SYSTEMS

A generalised computer program has been developed to
compare all the four systems in terms of the state points,
the mass of adsorbent required, heat exchanger capacities
and power requirement. Interactive features have been added
to the program to help the execution of program. The name
of the program is MAIN.FOR and it has been stored in the
tape D-186. In future, same program can be modified for
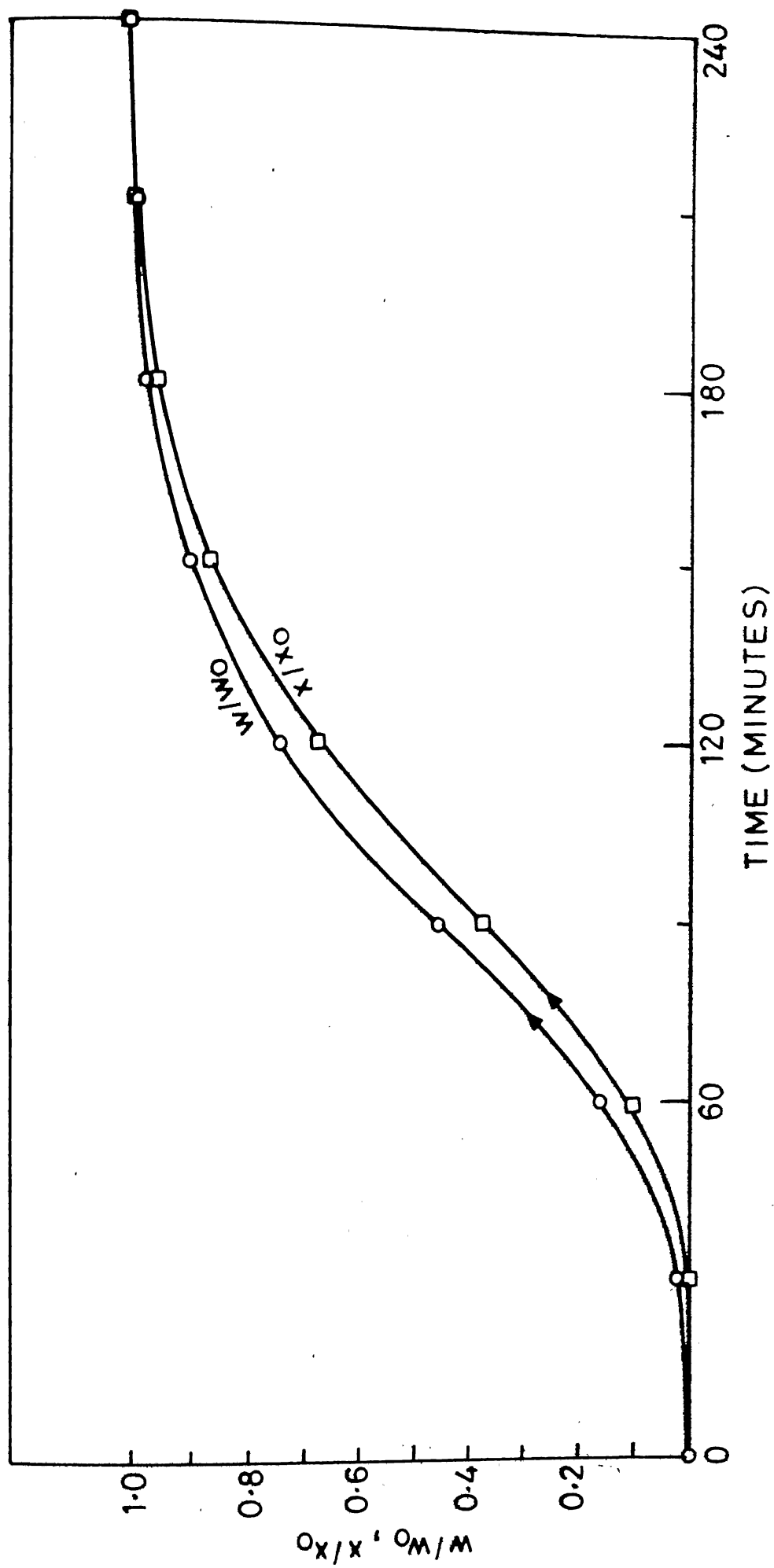studying the economics of the system in details.

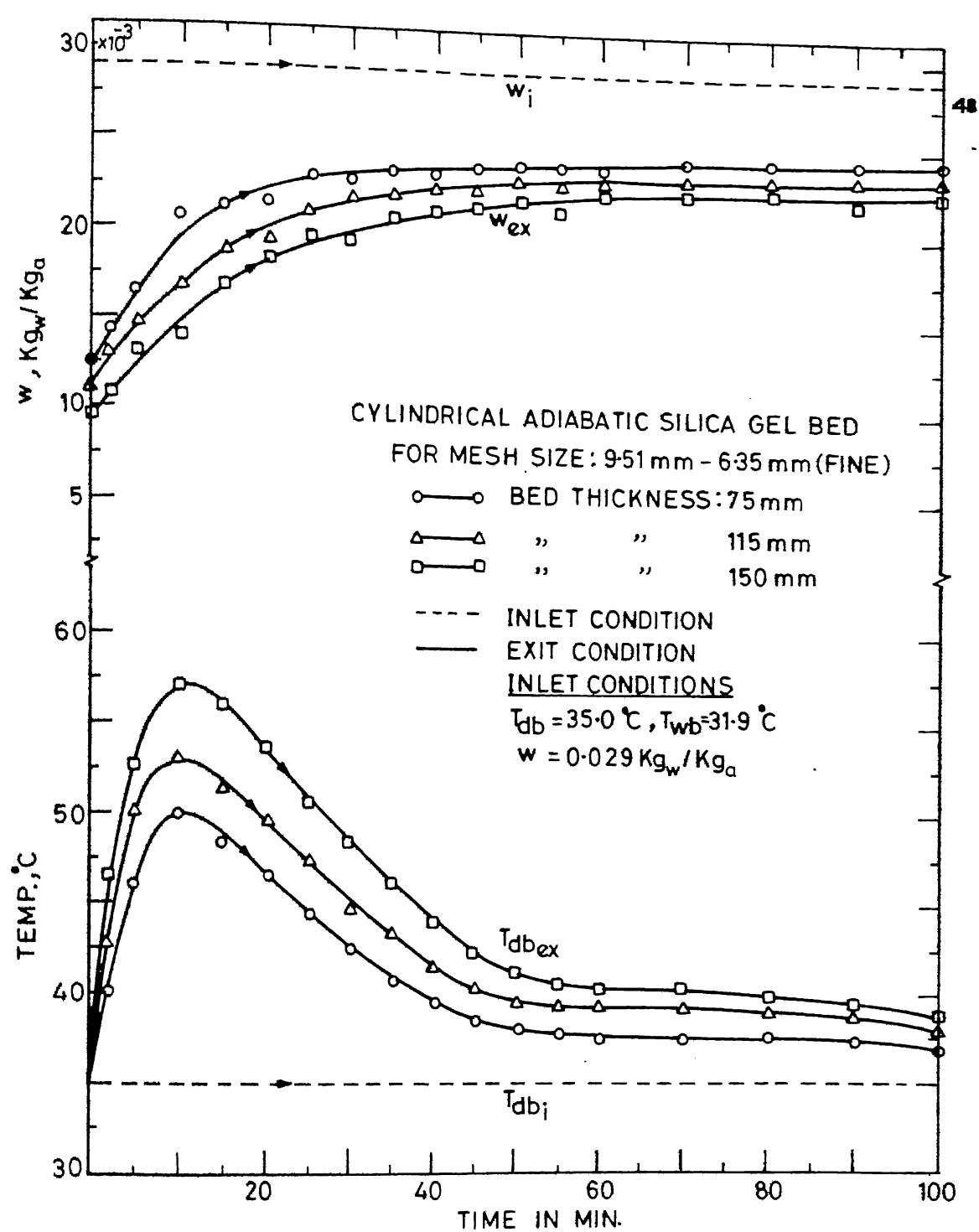FIG.5·1 THEORETICAL VARIATION OF w/w_0 AND x/x_0 WITH TIME FOR STATIONARY ISOTHERMAL ADSORBENT BED

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FIG.5·2 TIME WISE VARIATION OF $T_{db_{ex}}$ AND w_{ex} OF DEHUMIDIED AIR FOR DIFFERENT BED THICKNESSES

CYLINDRICAL ADIABATIC SILICA GEL BED
FOR MESH SIZE : 9·51 mm – 6·35 mm (FINE)

o——o BED THICKNESS : 75 mm
△——△   ,,   ,,   115 mm
□——□   ,,   ,,   150 mm
- - - - INLET CONDITION
———   EXIT CONDITION
INLET CONDITIONS
T_{db} = 35·0 °C , T_{wb} = 31·9 °C
w = 0·029 Kg$_w$/Kg$_a$

CYLINDRICAL ADIABATIC SILICA GEL BED

MESH SIZE: 12·7mm – 9·51 mm (MEDIUM)

○———○ BED THICKNESS: 75mm

△———△   "   "   115 mm

□———□   "   "   150 mm

– – – – INLET CONDITIONS

——— EXIT CONDITIONS

INLET CONDITIONS

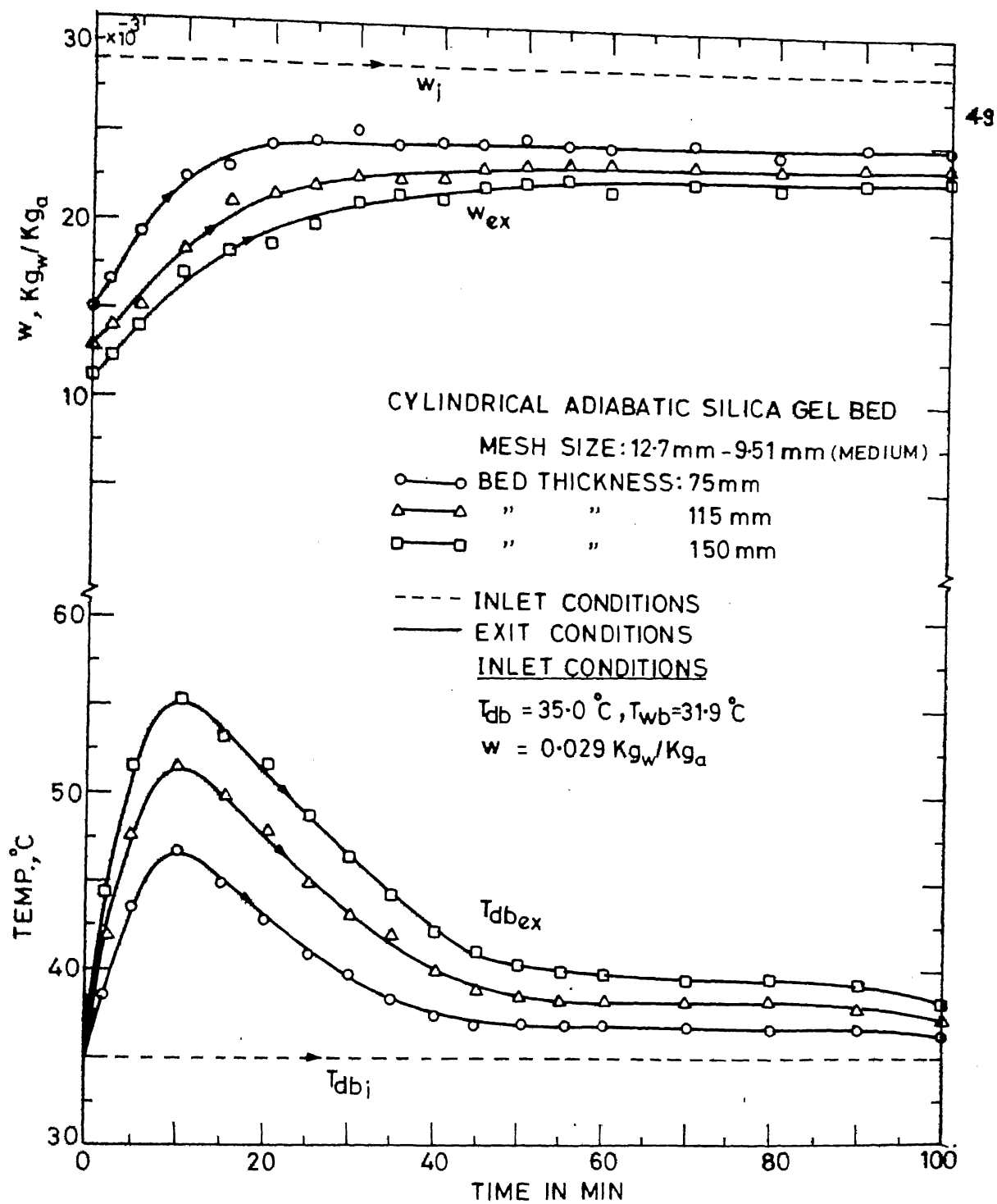$T_{db} = 35.0\ ^\circ C$, $T_{wb} = 31.9\ ^\circ C$

$w = 0.029\ Kg_w/Kg_a$

FIG·5·3 TIME WISE VARIATION OF $T_{db_{ex}}$ AND w_{ex} OF DEHUMIDIFIED AIR FOR DIFFERENT BED THICKNESSES
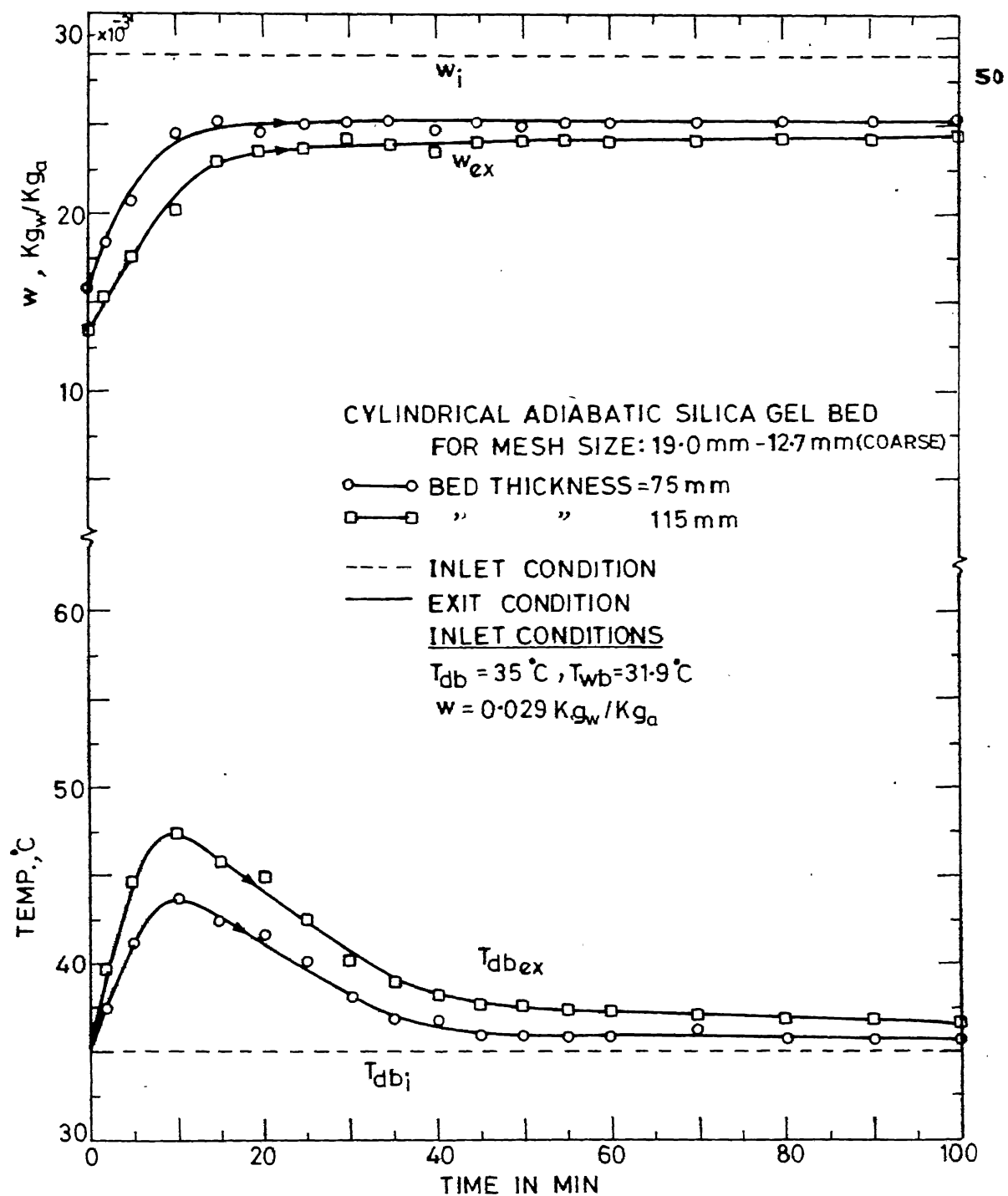
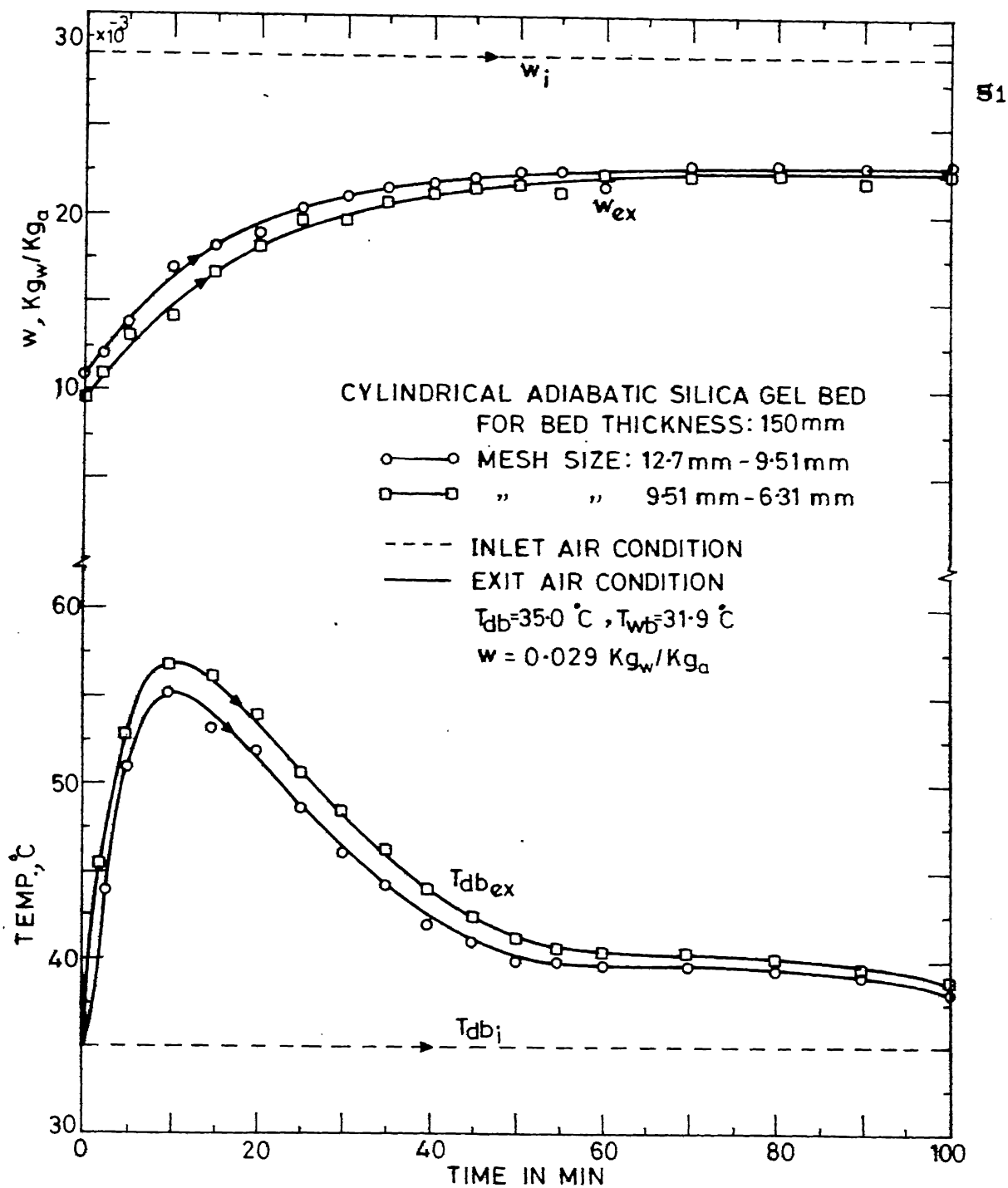FIG. 5.4 TIME WISE VARIATION OF $T_{db_{ex}}$ AND w_{ex} OF DEHUMIDIFIED AIR FOR DIFFERENT BED THICKNESSES

FIG.5.5 TIME WISE VARIATION OF $T_{db_{ex}}$ AND w_{ex} OF DEHUMIDIFIED AIR FOR DIFFERENT MESH SIZES
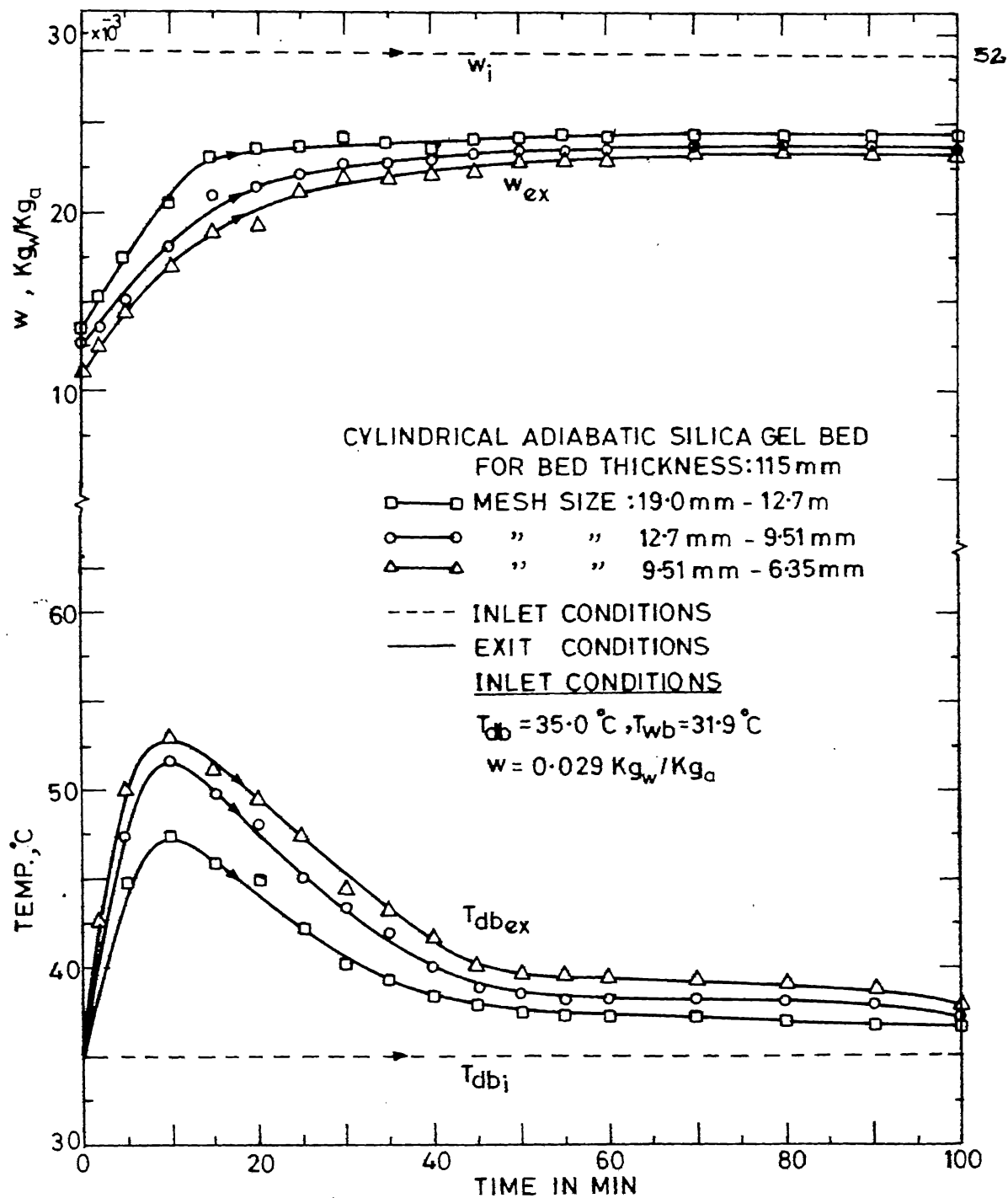
FIG·5·6 TIME WISE VARIATION OF T_{db_e} AND w_{ex} OF DEHUMIDIFIED AIR FOR DIFFERENT MESH SIZES

Chart content:

CYLINDRICAL ADIABATIC SILICA GEL BED
FOR BED THICKNESS: 115 mm
□——□ MESH SIZE : 19·0 mm - 12·7 m
○——○ " " 12·7 mm - 9·51 mm
△——△ " " 9·51 mm - 6·35 mm
---- INLET CONDITIONS
—— EXIT CONDITIONS
INLET CONDITIONS
T_{db} = 35·0 °C , T_{wb} = 31·9 °C
w = 0·029 Kg_w / Kg_a

y-axis (upper): w , Kg_w / Kg_a (×10⁻³), with w_i and w_{ex} labelled
y-axis (lower): TEMP., °C, with $T_{db_{ex}}$ and T_{db_i} labelled
x-axis: TIME IN MIN

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FIG.5.7 TIME WISE VARIATION OF $T_{db_{ex}}$ AND w_{ex} OF DEHUMIDIFIED AIR
FOR DIFFERENT MESH SIZES

Text within the figure:

CYLINDRICAL ADIABATIC SILICA GEL BED
FOR BED THICKNESS : 75 mm
○——○ MESH SIZE : 9.51 mm – 6.31 mm
△——△   „   „   12.7 mm – 9.51 mm
□——□   „   „   19.0 mm – 12.7 mm
----- INLET CONDITIONS
——— EXIT CONDITIONS
INLET CONDITIONS
T_{db} = 35.0 °C , T_{wb} = 31.9 °C
w = 0.029 Kg_w/Kg_a

Axis labels: w, Kg_w/Kg_a ; TEMP., °C ; TIME IN MIN

30×10^{-3}

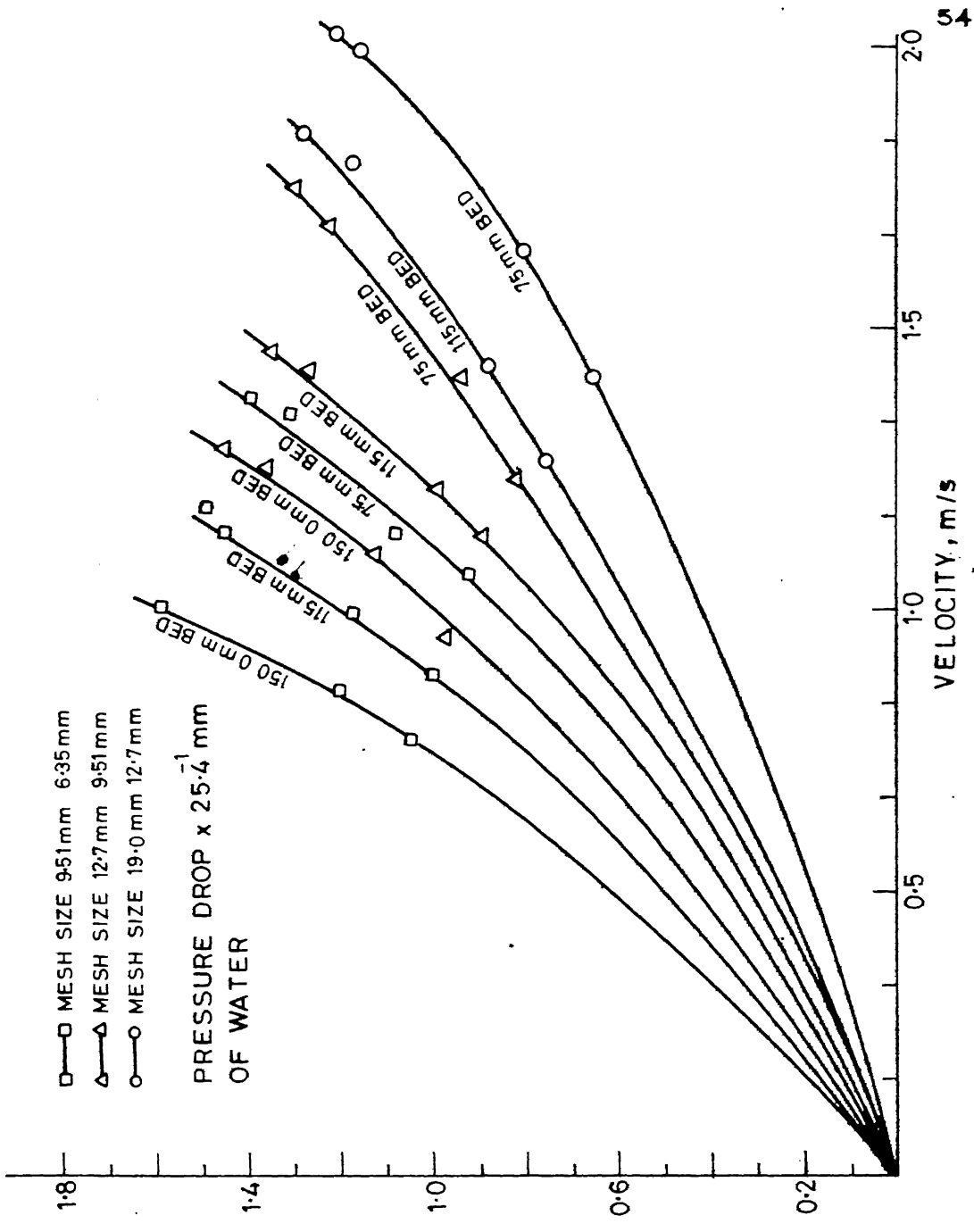w_i ; w_{ex} ; $T_{db_{ex}}$; T_{db_i}

53

FIG. 5.8 VARIATION OF PRESSURE DROP ACROSS ADSORBENT BED WITH RESPECT TO VELOCITY, MESH SIZE, AND BED THICKNESS

Table 5.1(a)

Comparative Results for Major Coastal Cities

Inside design condition. 28°C, 61.0%, Temp. rise in the room = 6.0°C,

Humidity ratio rise in the room = 0.0025 kg_w/kg_a, ε = 0.86,

Temperature: °C, Sp. humidity w: kg_w/kg_a, RH%

CITY	Outside Design Condition	SYS-TEM	1 T	1 w	2 T	2 w	3 T	3 w	4 T	4 w	5 T	5 w	6 T	6 w	7 T	7 w	8 T	8 w	9 T	9 w	10 T	10 w	EVAP T	EVAP w
															STATE POINTS									
BOMBAY	T_{db} = 30.5 T_{wb} = 27.1 R.H. = 77.0	I	30.50	0.0214	65.60	.0074	33.78	.0074	22.09	.0122	28.09	.0147	22.06	.0123	26.067	.0148	–	–	–	–	–	–	–	–
		II	30.50	0.0214	47.90	.0144	33.11	.0144	47.90	.0085	31.11	.0083	42.00	.0089	30.22	.0089	22.06	.0124	28.06	.0149	–	–	–	–
		III	30.50	0.0214	42.00	.0167	32.22	.0167	42.00	.0128	32.22	.0128	27.78	–	29.33	.0120	–	–	15.37	.0110	17.99	–	12.00	10.37
		IV	30.50	0.0214	28.00	.0145	28.50	.0145	38.15	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
		V*	30.50	0.0214	28.00	.0145	28.50	.0159	–	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
CAL-CUTTA	T_{db} = 32.4 T_{wb} = 28.5 R.H. = 74.0	I	32.40	0.0232	73.50	.0069	34.90	.0069	22.03	.0121	28.03	.0146	21.99	.0121	27.99	.0146	–	–	–	–	–	–	–	–
		II	32.40	0.0232	52.80	.0150	35.46	.0150	52.80	.0061	31.77	.0081	46.00	.0085	30.78	.0085	22.01	.0120	28.01	.0145	–	–	–	–
		III	32.40	0.0232	46.00	.0177	34.44	.0177	46.00	.0130	34.44	.0130	29.28	–	30.80	.0120	–	–	15.27	.0109	17.99	–	12.00	10.27
		IV	32.40	0.0232	28.00	.0145	26.89	.0145	39.44	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
		V*	32.40	0.0232	28.00	.0145	28.89	.0162	–	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
MADRAS	T_{db} = 35.2 T_{wb} = 28.5 R.H. = 63.0	I	35.20	0.0220	73.40	.0069	34.96	.0060	22.09	.0121	28.09	.0146	22.056	.0124	28.05	.0149	–	–	–	–	–	–	–	–
		II	35.20	0.0220	53.80	.0145	37.99	.0145	53.80	.0083	31.96	.0083	47.70	.0085	22.02	.0122	28.02	.0147	22.08	.0147	–	–	–	–
		III	35.20	0.0220	47.70	.0170	37.075	.0170	47.70	.0127	37.07	.0127	29.84	–	31.27	.0120	–	–	15.37	.0110	18.15	–	12.00	10.336
		IV	35.20	0.0220	28.00	.0145	29.45	.0016	89.41	.012	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
		V*	35.20	0.0220	28.00	.0145	29.45	.0016	–	–	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
TRIVEN-DRUM	T_{db} = 28.2 T_{wb} = 25.7 R.H. = 82.2	I	28.20	0.0199	58.60	.0078	32.68	.0078	22.05	.0121	28.05	.0146	22.00	.0123	28.00	.0148	–	–	–	–	–	–	–	–
		II	28.20	0.0199	43.10	.0139	31.43	.0139	43.10	.0088	30.32	.0088	38.20	.0090	29.58	.0090	21.99	.0122	27.99	.0147	–	–	–	–
		III	28.20	0.0199	38.20	.0159	29.70	.0159	38.20	.0124	29.70	.0124	26.20	–	27.81	.0120	–	–	15.45	.0111	17.96	–	12.00	10.45
		IV	28.20	0.0199	28.00	.0145	28.04	.0156	36.94	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
		V*	28.20	0.0199	28.00	.0145	28.04	.0156	–	–	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
	For worst condition T_{db} = 35.0 T_{wb} = 31.0 R.H. = 75.0	I	35.00	0.0272	88.50	.0060	37.13	.0060	21.98	.0121	27.98	.0146	22.01	.0122	28.01	.0147	–	–	–	–	–	–	–	–
		II	35.00	0.0272	61.40	.0165	38.96	.0165	61.40	.0076	33.06	.0078	52.50	.0082	31.72	.0082	22.00	.0122	28.00	.0147	–	–	–	–
		III	35.00	0.0272	52.50	.0141	37.62	.0201	52.50	.0141	37.62	.0141	31.80	–	33.32	.0120	–	–	15.05	.0107	17.92	–	12.00	10.05
		IV	35.00	0.0272	28.00	.0145	29.42	.0170	41.95	.0120	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–
		V*	35.00	0.0272	28.00	.0145	29.42	.0145	–	–	22.00	.0120	–	–	–	–	–	–	–	–	–	–	–	–

V* Conventional system.

Table 5.1(b)

Comparative Results for Components Material and Power Requirement
Humidification Period = 2 Hrs.

CITY	SYSTEM	Mass of Air kg/min.	Mass of Adsorbent kg				Heat Exchanger Capacity, kJ/min.			Power Required						Capacity of cooling coil kJ/kg
			First Bed	Second Bed	Third Bed	Total	HE1	HE2	HE3	H_1	H_2	Ref.kW	Fan kW	Reheat.kW	Total kW	
BOMBAY	I	16.751	172.641	-	-	172.641	542.27	-	-	0.78	-	-	0.348	-	0.3525	-
	II	16.751	56.396	77.58	-	133.985	255.159	286.59	-	0.735	-	-	0.348	-	0.3525	-
	III	16.75	33.091	36.687	51.849	121.627	169.321	168.162	201.116	0.72	-	-	0.348	-	0.3525	-
	IV	16.755	30.407	-	-	30.407	151.54	-	-	0.85	0.8	0.581	0.348	-	0.929	126.068
	V*	16.755	-	-	-	-	-	-	-	-	-	1.605	-	1.147	2.752	210.000
CALCUTTA	I	16.753	202.79	-	-	202.79	657.189	-	-	0.793	-	-	0.352	-	0.352	-
	II	16.750	68.371	103.704	-	172.075	299.518	358.742	-	0.745	-	-	0.352	-	0.352	-
	III	16.750	41.344	48.99	72.240	162.581	200.635	199.015	259.805	0.720	-	-	0.352	-	0.352	-
	IV	16.755	34.012	-	-	34.012	148.40	-	-	0.850	0.8	0.697	0.352	-	1.044	151.294
	V	16.755	-	-	-	-	-	-	-	-	-	1.708	-	1.147	2.855	210.000
MADRAS	I	16.753	214.132	-	-	214.132	654.361	-	-	0.791	-	-	0.356	-	0.356	-
	II	16.750	70.878	114.546	-	185.424	272.79	372.79	-	0.760	-	-	0.356	-	0.356	-
	III	16.750	43.88	56.108	80.525	180.513	164.140	182.776	284.657	0.734	-	-	0.356	-	0.356	-
	IV	16.755	33.148	-	-	33.148	139.845	-	-	0.850	0.8	0.735	0.356	-	1.090	159.40
	V*	16.755	-	-	-	-	-	-	-	-	-	1.693	-	1.100	2.793	210.00
TRIVANDRUM	I	16.752	152.32	-	-	152.32	442.06	-	-	0.760	-	-	0.344	-	0.344	-
	II	16.750	46.968	56.089	-	103.057	218.304	218.245	-	0.725	-	-	0.344	-	0.344	-
	III	16.750	27.485	27.811	37.800	93.096	147.03	146.15	147.24	0.700	-	-	0.344	-	0.344	-
	IV	16.755	27.277	-	-	27.277	157.007	-	-	0.850	0.8	0.460	0.344	-	0.804	99.682
	V*	16.755	-	-	-	-	-	-	-	-	-	1.511	-	1.155	2.666	210.00
FOR WORST CONDITIONS	I	16.750	263.55	-	-	263.55	755.00	-	-	0.820	-	-	0.356	-	0.356	-
	II	16.750	91.246	153.52	-	244.76	388.628	483.136	-	0.770	-	-	0.356	-	0.356	-
	III	16.750	56.175	70.26	108.076	234.519	259.20	256.52	354.506	0.750	-	-	0.356	-	0.356	-
	IV	16.755	41.50	-	-	41.50	148.30	-	-	0.850	0.8	0.897	0.356	-	1.253	194.58
	V*	16.755	-	-	-	-	-	-	-	-	-	1.915	-	1.166	3.081	210.00

V* – Conventional System

CHAPTER VI

CONCLUSIONS AND SUGGESTIONS

6.1 CONCLUSIONS

From the present experimental results and system analysis the following conclusions have been put forth:

1. The results of the computer program developed for the study of isothermal adsorbent bed agree with the theoretical available results.

2. The time period for effective dehumidification was found to be of the order of 20 minutes due to smaller thickness of the bed and the regeneration should be done thereafter.

3. For a given velocity through a silica gel bed of given mesh size, the rate and amount of humidification increases with bed thickness.

4. For a given velocity through a silica gel bed of given mesh size, the time required for saturation of the bed increases with the bed thickness.

5. For a given velocity through silica gel bed of given bed thickness, the rate and amount of dehumidification increases as the mesh size of the silica gel reduces.

6. For a given velocity through silica gel bed of given thickness, time required for the saturation of the bed increases as mesh size of silica gel reduces.

7. For different combinations of mesh size and bed thickness the relation between pressure drop and velocity through the bed is of parabolic nature.

8. For a given value of velocity and bed thickness the pressure drop for lower grade silica gel is more than the coarse grade silica gel.

9. The pressure drop across the bed increases with the bed thickness for given values of velocity and mesh size.

10. Out of the four air conditioning systems developed, system IV was found to give the best performance. It is found to be a good substitute for the conventional vapour-compression air conditioning system as applied to hot and humid environments.

11. As number of stages in the system are increased mass of adsorbent required decreases and the number of components required increases.

6.2 SUGGESTIONS FOR FUTURE WORK

In the time bound M.Tech. program, it was not possible to go into the depth of the investigation due to involvement of large number of variables and large time involved in the fabrication and commissioning of the experimental set-up. Therefore following suggestions are put forth for future investigation.

1. The effect of face velocity on the dehumidification may be studied maintaining mesh size and bed thickness constant.

2.   Economics of the whole system should be studied and the results should be analysed in the view of increasing cost of electrical energy.

3.   The performance of a prototype system should be studied.

4.   Heat removed in heat exchangers, and condenser (System IV) can be utilised for regeneration of silica gel.

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APPENDIX - B

EQUATIONS AND PROCEDURES USED FOR PREDICTION OF

VARIOUS QUANTITIES FOR THE COMPUTER PROGRAM OF SYSTEM

ANALYSIS

(1) $\quad \text{Log } (p_s) = \dfrac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_s T^3 + C_6 \log_e T$ [23]

This equation gives value of saturation vapour pressure p_s in

Pascal for a given value of T.

For: 0 - 200°C

T : K

$C_1 = -5800.2206, \; C_2 = 0.13914993, \; C_3 = -0.048640239,$

$C_4 = 0.41764768 \times 10^{-4}, \; C_5 = -014452093 \times 10^{-7}, \; C_6 = 6.5459673$

(2) The vapour pressure at a particular state for given values of

T_{db} and T_{wb} is calculated from the well known Dr. Carrier's equation:

$$p_v = p_{wbs} - \frac{(p - p_{wbs})(t_{db} - T_{wb})}{1547 - 1.44\, T_{wb}}$$

T_{db} : °C, T_{wb} : °C, p : Atmospheric Pressure, bar

p_v : Vapour Pressure, bar,

(3) The enthalpy of moist air for known values of T and w is

given by

$\quad h = 1.004 \times T + w \times (2501.4 + 1.805 \times T)$

(4) The vapour pressure p_s for given value of T is also calculated

from [24]:

$$\log_e \frac{226.5}{p_s} = [7.21379 + (A + B.T)(T - 483.16)^2] \times [\frac{647.31}{T} - 1]$$

For : 0 - 210°C, p_s : kgf/cm^2, A : 1.1520×10^{-5},

B : -4.787×10^{-9}, T : Temperature, K

(5)   Equation relating moisture content x and K

[Ref. pp. 38, Chapter IV of this thesis]

$$Z = 10 \ x \ K$$

$$x = A + BZ + CZ^2 + DZ^3 + EZ^4$$

where,

A : 0.3974844×10^{-1}, B : 0.2118460×10^{-2},

C : 0.9908365×10^{-2}, D : 0.5626685×10^{-3},

E : $-0.1387267 \times 10^{-3}$.

(6)   Properties of R-22 [25]

T : K,   t : $^{\circ}$C

$$s_f(T) = 0.181132 + 0.43667 \times \frac{t}{100} - 0.0596756 \times (\frac{t}{100})^2$$
$$-0.0234343 \times (\frac{t}{100})^3 + 0.0638047 (\frac{t}{100})^4$$

$$h_g(T) = 251.106 + 35.4577 \times (\frac{t}{100}) - 19.4993 (\frac{t}{100})^2$$
$$-7.62005 (\frac{t}{100})^3 - 11.6756 (\frac{t}{100})^4$$

$$h_f(T) = 46.2102 + 1.20394 \times t + 6.828 (\frac{t}{100})^2$$
$$-8.99387 (\frac{t}{100})^3 + 20.0612 (\frac{t}{100})^4$$

where,

$s_f(T)$: Saturation liquid entropy at T, kJ/kg.K

$h_g(T)$: Saturation vapour enthalpy at T, kJ/kg

$h_f(T)$: Saturation fluid enthalpy at T, kJ/kg

$$C_{pg} = 0.70714 + 0.0029529 [(T-283.15) + 0.010472 (T-283.15)^2]$$

For $283.15 \leq T \leq 328.15$

$$C_{pg} = 0.60 + 0.00005246 [(T-228.15) + 0.043686 \times (T-228.15)^2]$$

For $233.15 \leq T \leq 283.15$

$$p = 4.98105 + 0.161746 \ t + 0.0019565 \ t^2$$
$$+ 9.8434 (\frac{t}{100})^3 + 2.22194 (\frac{t}{100})^4$$

$$\eta_c = [1.13623 + 0.113289 \ r - 0.0334529 \ r^2$$
$$+ 4.8675 (\frac{r}{10})^3 - 2.135 (\frac{r}{10})^4]^{-1}$$

where r is the compression ratio, p : bar.

APPENDIX – C

STATE POINTS FOR SYSTEM I WITH THE NUMBER OF ITERATIONS

T : °C,   w : kg_w/kg_a

Refer Fig. 4.1.   Table C-1:

No. of Iterations	STATE 1		STATE 2		STATE 3		STATE 4		STATE 5	
	T_1	w_1	T_2	w_2	T_3	w_3	T_4	w_4	T_5	w_5
1	35.00	0.027	88.50	0.0060	43.025	0.0060	25.126	0.0142	31.126	0.0167
2	35.00	0.027	88.50	0.0060	39.732	0.0060	23.411	0.0130	29.411	0.0155
3	35.00	0.027	88.50	0.0060	38.274	0.0060	22.620	0.0125	28.620	0.0150
4	35.00	0.027	88.50	0.0060	37.602	0.0060	22.248	0.0123	28.240	0.0148
5	35.00	0.027	88.50	0.0060	37.286	0.0060	22.072	0.0122	28.072	0.0147
6	35.00	0.027	88.50	0.0060	37.136	0.0060	21.988	0.0121	27.988	0.0146
Steady State	35.00	0.027	88.50	0.0060	37.136	0.0060	21.988	0.0121	27.988	0.0146